

A review of design issues specific to hypersonic flight vehicles
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Abstract

This paper provides an overview of the current technical issues and challenges associated with the design of hypersonic vehicles. Two distinct classes of vehicles are reviewed; Hypersonic Transports and Space Launchers, their common features and differences are examined. After a brief historical overview, the paper takes a multi-disciplinary approach to these vehicles, discusses various design aspects, and technical challenges. Operational issues are explored, including mission profiles, current and predicted markets, in addition to environmental effects and human factors. Technological issues are also reviewed, focusing on the three major challenge areas associated with these vehicles: aerothermodynamics, propulsion, and structures. In addition, matters of reliability and maintainability are also presented. The paper also reviews the certification and flight testing of these vehicles from a global perspective. Finally the current stakeholders in the field of hypersonic flight are presented, summarizing the active programs and promising concepts.

Keywords

Hypersonic Transport, Space Launcher, Design review

Abbreviations

- **AETB:** Alumina Enhanced Thermal Barrier
- **AFRSI:** Advanced Flexible Reusable Surface Insulation
- **AOA:** Angle of Attack
- **CFD:** Computational Fluid Dynamics
- **CG:** Centre of Gravity
- **EASA:** European Aviation Safety Agency
- **EMU:** Extravehicular Mobility Unit
- **ESA:** European Space Agency

- **EMU:** Extravehicular Mobility Unit
- **EVA:** Extravehicular Activity
- **FAA:** Federal Aviation Administration
- **FRCI:** Silicon Fibrous Refractory Composite Insulation
- **FRSI:** Felt Reusable Surface Insulation
- **GPS:** Global Positioning System
- **GSO:** Geostationary Orbit
- **GTO:** Geostationary Transfer Orbit
- **HRSI/LRSI:** High/Low Temperature Reusable Surface Insulation (tiles)
- **ICAO:** International Civil Aviation Organization
- **I_{sp} :** Specific Impulse
- **ISS:** International Space Station
- **L/D:** Lift to drag ratio
- **LACE:** Liquid Air Cycle Engine
- **LEO:** Low Earth Orbit
- **M:** Mach number
- **MHD:** Magneto-hydrodynamic
- **MTSO:** Multiple Stage to Orbit
- **NGSO:** Non-Geostationary Orbit
- **ODS:** Oxide Dispersion Strengthened (alloy)
- **OMS:** Orbital Manoeuvring System
- **RCC:** Reinforce Carbon-carbon Composite
- **RCS:** Reaction Control System
- **ROCCI:** Refractory Oxidation Resistant Ceramic Carbon Insulation
- **SHARP:** Slender Hypervelocity Aerothermodynamic Research Probe
- **SPFI:** Surface Protected Flexible Insulation
- **SSO:** SpaceShipOne
- **SSTO:** Single Stage to Orbit
- **STS:** Space Transportation System
- **TPS:** Thermal Protection System
- **TSTO:** Two Stage to Orbit
- **TUFI:** Toughened Uni-Piece Fibrous Insulation
- **TUFROC:** Toughened Uni-piece Fibrous Reinforced Oxidation-resistant Composite
- **USAF:** United States Air Force

1.0 Introduction

Currently most large airframe manufacturers are focusing on developing more efficient, cheaper, greener aircraft designs.

There are, however, other requirements which have to be considered in addition to economic and environmental aspects. The ability in itself, to drastically reduce travelling time, could justify the existence of a Hypersonic Transport for applications such as emergency response, time critical business trips, not to mention military applications. A typical Hypersonic Transport is estimated to travel from Tokyo to Los Angeles in only 110 minutes [1.]. While not fundamentally different, another distinct form of application for hypersonic flight is the Space Launch System. Compared to contemporary space access technology, Space Launchers offer a significant advantage: they can reach, operate in and return from orbit without expending the vehicle. Expendable launch vehicles add significant overhead cost to any space access mission, as the cost of launching the payload includes the acquisition cost of the launcher. Also, time between launches is limited by the availability of new launch vehicles, which potentially prevents rapid response missions from being performed.

To develop a successful hypersonic vehicle, it is not enough to concentrate on the vehicle itself, but rather it has to be looked at from a systems point of view. This ensures that not only performance goals are met, but also safety, security, maintainability, operational flexibility, reliability and sustainability as well.

This paper aims to investigate the challenges associated with the design of hypersonic vehicles. Past designs and concepts, current solutions and developments and likely future trends are considered to present the state of the art and the possible vehicles of tomorrow. The design of this special class of vehicle is investigated from a multidisciplinary point of view.

A brief historical background of the hypersonic vehicles is presented, highlighting the successful concepts. Operational issues are then investigated, dealing with both economic and environmental questions, from both the users and global point of view. A summary of the technological issues to overcome is also presented, highlighting the aerothermodynamics and propulsion aspects, the two main challenges with hypersonic vehicles. In addition to these, the topics of reliability and maintainability are also considered. Further challenges, testing and prediction methods, along with the current state of certification issues are also covered. Finally, a list of stakeholders is presented along with current projects to show the state of the art in the field of hypersonic vehicles.

2.0 HISTORICAL BACKGROUND

Surprising though it may seem, the concept of hypersonic flight surfaced relatively early. In the late 1930s Eugene Sänger had conceived a rocket-powered boost-glide vehicle in Germany, named Silbervogel [2.] (Silver bird) which could have been used to attack the United States, and land safely in Japan afterwards. Although the project was cancelled by the Reich Air Ministry in 1941, Sänger never gave up his dream, and continued working on the concept, paving the way for many aerospace vehicle designs to come.

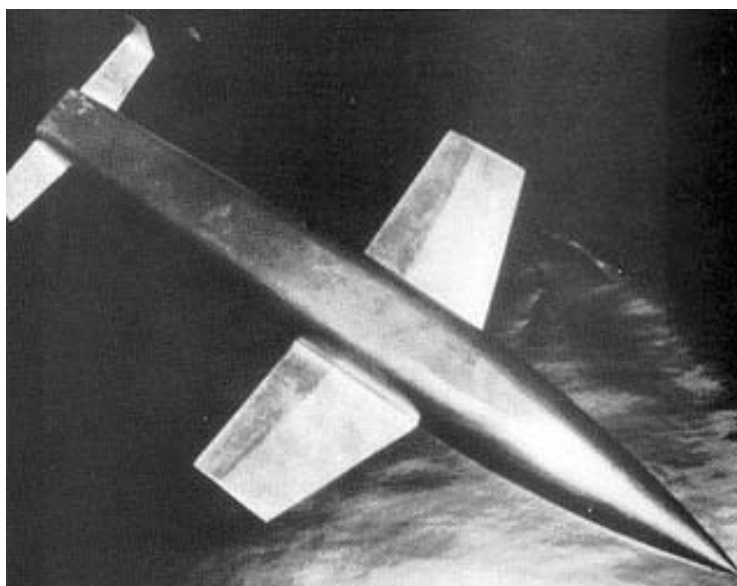


Figure 1. Sänger Silbervogel (source: [3.])

After the thirties, many concepts were investigated, but due to lack of funding, or technological immaturity, the vast majority of these remained on the drawing board. Up to now only 5 aerospace vehicles have made it into space and returned safely, these are: X-15, Space Shuttle, Buran, SpaceShipOne and X-37. It has to be noted, that the generally accepted definition of space means an altitude above the Kármán line, at least 100km.

The pioneer in the field of hypersonic flight was the North American Aviation X-15 [4.]. The program began in 1954, with the first flight occurring on the 8th of June, 1959. There were 3 test aircraft manufactured, taking part in a total number of 199 flights. They were dropped at high altitudes from a modified B-52 aircraft, after which their own engines would start, and the flight testing phase could begin. The maximum altitude reached was 107.96 km (Flight 91), while the highest speed attained was 7,273 km/h (Flight 188). The X-15 provided large amounts of high speed flight data, including lift distribution and control systems effectiveness.

The Space Shuttle program (formerly known as the Space Transportation System) was initiated in 1969, when President Richard Nixon formed the Space Task Group. The official approval (and government funding) of the STS program began in 1972, with the first powered flight taking place on 12th April 1981. Although the program run until 2011, and a total of 135 missions were flown, the STS program did not satisfy all of the original requirements, especially in terms of cost and turnaround times. Also, the Shuttle system was only partially reusable, because of the expendable fuel tank, and the recoverable boosters required almost full reconstruction between each launch, resulting in high cost, and man-hour requirements. In addition to launching a maximum of 25ton payload to LEO, the Shuttle had the additional benefit of performing maintenance tasks in orbit, and it could also return objects from space when required. The Space Shuttle re-entered the atmosphere at around the speed of M 25.

The Buran was the Soviet answer to the Space Shuttle. Shortly after completing one unmanned autonomous flight on 15th November 1988, the program was cancelled due to lack of funding. The orbiter itself was lighter than the Space Shuttle, as it didn't have the main engines mounted on the orbiter. This is because the Buran was launched attached to an Energia rocket, which provided all the thrust, as opposed to the booster and tank configuration of STS. It could carry 30tons to LEO, and return with 20ton payload on board. Several orbiters were planned to be manufactured, however at the termination of the program, only one flight capable orbiter existed: 11F35 K1 "Buran" (Буран, meaning Snowstorm or Blizzard). It was destroyed in an accident in 2002, when the storage hangar collapsed on it due to lack of maintenance. An almost completed orbiter, 11F35 K2 "Ptichka" (Птичка, meaning Little Bird), is currently in Baikonur.

The Scaled Composites SpaceShipOne was the winner of Ansari X-Prize competition, by being the first aerospace vehicle to launch three people to at least 100 km altitude and twice within two weeks. SpaceShipOne, launched from the mother ship White Knight, successfully satisfied the competition requirements on the 4th of October 2004, for which they received the prize of \$10 million. Since then Burt Rutan's company has developed the successor SpaceShipTwo for space tourism with provisional plans for the SpaceShipThree orbital transport. The first SpaceShipTwo crashed during a test flight on 31 October 2014. The highest speed SSO reached was only Mach 3, which does not make it a hypersonic vehicle, but the environment it operates in is similar to an intended hypersonic vehicle and thus it makes a good reference point.

The Boeing X-37 Orbital Test Vehicle is an unmanned aerospace vehicle, being developed since 1999. The first flight took place on the 22nd of April 2010, when it was launched on top of an Atlas V rocket. It remained in orbit until the 3rd of December 2010, when it returned to the atmosphere and landed safely. The second launch took place on 5th of March, 2011, lasting 15 months, the vehicle returning on 16th of June, 2012. There was also a third launch on 11th of December, 2012, which successfully returned to

Vandenberg Air Force Base on the 17th of October, 2014. The exact nature of their orbital mission is unknown at the moment. There are future plans of a larger manned version, but most of the information regarding the X-37 is still classified. The re-entry speed is similar to the Space Shuttle, around M25 [5.]. A similar concept to the X-37C is Cranfield University's SL-12 [6.]. The X-37B with its payload adapter attached and encased in its fairing before launch is shown in Figure 2.



Figure 2: Boeing X-37B Orbital Test Vehicle in its fairing (source: [7.])

Up to this day no hypersonic transport vehicles have been flown or even constructed. While many concepts exist, most of them are lacking funding, mainly because they utilise technology of a low level of maturity that poses significant risk for the project, or simply due to the considerable cost associated with developing a hypersonic vehicle. Even for those vehicles which have flown successfully, such as the Space Shuttle and the Buran, their existence can to some extent, be attributed to the Cold War. If it weren't for the two

superpowers constantly trying to outdo the other in terms of technology, the billions of dollars/roubles spent on their space programs might not have been given so easily. Since the fall of the Soviet Union, the budgets of space programs have been cut drastically, which have been further reduced by the economic crisis of the past few years. As a result many projects were cancelled or abandoned (such as the Buran), and major players such as NASA suffer a shortage of funding in some fields. This led to the rise of privately owned companies such as Scaled Composites, who are incrementally developing their aerospace vehicles. No one however, now dares to embark upon such adventurous investments as the STS program, due to the amount of capital and high levels of risk involved. It will certainly require a major change in philosophy if hypersonic vehicles are to be seen in operation.

3.0 OPERATIONAL ISSUES

3.1 Mission profiles

One of the most significant differences between the Space Launchers and Hypersonic Transports is the type of missions they perform. Launchers are designed to place the vehicle into orbit using its main propulsion systems. The orbits achieved by these vehicles are always Low Earth Orbit (100km to about 2000km), but it is rare that any concept achieves more than 400 km (the ISS's orbit). Once in orbit, the vehicle performs the orbital part of the mission: deploy the payload, rendezvous with other objects, repair, recover, etc. Either the same main propulsion systems or a dedicated Orbital Manoeuvring System (OMS) is used for orbital adjustments, as required by the mission, then finally to deorbit. Once the vehicle has re-entered Earth's atmosphere, it can land as a glider or use its propulsion system to reach the landing site, as applicable to the concept. Powered landing concepts are rare as it involves launching additional mass into space. Also the carriage of fuel during re-entry is a safety hazard. As the main propulsion

systems are principally utilized to reach the required speed and altitude, this class of hypersonic vehicles are often referred to as ‘accelerators’.

Similar to rockets, Space Launcher concepts can be built up from more than one vehicle, or stages. The holy grail of launcher technology, the Single Stage To Orbit (SSTO) vehicle, could provide true aircraft-like operations, but is also the most challenging, mainly due to the very high fuel fraction required. A typical example is the Reaction Engines Skylon. Two Stage To Orbit (TSTO) or Multiple Stage To Orbit (MSTO) concepts have an accelerator lower stage, which takes-off carrying the upper stage(s), and reaches sufficient altitude and speed for separation, where the upper stage launches to orbit. The carrier then returns to the spaceport. These concepts allow the orbital upper stage to be much lighter, than a SSTO. Typical TSTO is the Virgin Galactic Space Ship One (and Two). Although it is not an orbital vehicle, but the X-43 demonstrates the concept of a MSTO vehicle, pictured in Figure 3. See Chapter 6.0 for the description of these vehicles.



Figure 3: MSTO vehicle example: X-43 (source: [8.])

In contrast to the Space Launcher, the Hypersonic Transport operates in a different way. The first part of the mission is similar, as an acceleration phase is used to attain the required speed and altitude. Generally, hypersonic speeds are considered to be Mach 5 and above, while cruise altitudes are usually 80,000 feet and above, to avoid excessive heat build-up due to skin friction, and excessive structural loads. Once this set cruise condition is achieved, the vehicle operates as a conventional airliner, albeit much faster. Contrary to the launcher, where once in orbit there is no perceptible drag (unless a significant amount of time is spent in orbit), the transport has to provide thrust throughout the cruise to sustain these high speeds: thus they are also known as 'sustainers'. It can be seen however, that there is no reason why a transport could not reach such speeds and altitudes where it is able to enter orbit, and does not need to exert thrust throughout the cruise. There are indeed many concepts following this approach, either making a

single orbital insertion and deorbit (the process of a single insertion and deorbit is often referred as a “jump” or “boost”) or multiple shorter jumps. The latter is often referred to as a “boost-glide” vehicle, a prominent example is Sänger’s original concept. It is arguable whether these vehicles truly belong to the Hypersonic Transport category, as they basically perform the function of a Space Launcher.

Unlike the operation of a conventional airliner, hypersonic vehicles, especially Space Launchers are significantly affected by the location of the airport (spaceport or launch site). This is because an object on the Earth’s surface moves with a speed equivalent to the tangential velocity of that latitude due to the Earth’s rotation. As a result, vehicles launched from the equator require considerably less energy to achieve specific orbits than those launched from the poles. Obviously this is only beneficial when the inclination of the orbit is within $\pm 90^\circ$; in the case of polar and retrograde orbits this bonus becomes a penalty. However for many applications this can be used to significantly reduce the amount of fuel and the size of the vehicles; it is not surprising that many launch sites capitalize on this. Table 1 shows some major launch sites and prospective spaceports with their corresponding latitudes. In practice, the sites are also constrained by national boundaries.

Table 1: Major launch sites and spaceports

| Owner | Launch sites | Location | Latitude |
|---------------|--|-----------------|----------|
| China | Xichang | China | 28.2° N |
| ESA | Kourou | French Guyana | 5.2° N |
| India | Sriharikota | India | 13.9° N |
| International | Sea Launch – Ocean Odyssey | Pacific Ocean | Various |
| Japan | Tanegashima | Japan | 30.2° N |
| Russia | Baikonur | Kazakhstan | 45.6° N |
| Russia | Plesetsk | Russia | 62.8° N |
| Sweden | Esrange Space Center; Spaceport Sweden | Sweden | 67.9° N |
| USA | Spaceport America | New Mexico, USA | 33.0° N |

| | | | |
|-----|---------------------------------------|-----------------|---------|
| USA | Cape Canaveral (Kennedy Space Center) | Florida, USA | 28.5° N |
| USA | Vandenberg Air Force Base | California, USA | 34.7° N |

Contrary to expandable launch vehicles, many hypersonic concepts, especially two stage to orbit configurations have the potential to reach different latitudes before the orbital boost phase: this could increase flexibility in terms of the possible orbits achievable for a given configuration from a given spaceport and also enable the use of not so well positioned launch sites as bases of operation.

3.2 Market

The greatest challenge in defining a market for hypersonic vehicles is the fact that, apart from a few examples, there is no significant operational experience. Estimates are available however, the latest document published by the FAA [9.] predicts that up to 2022, about 30 new satellites will be launched each year. Figure 4 shows the predicted trend, divided between GSO and NGSO launches, while Figure 5 shows the total and average mass launch predictions up to 2015.

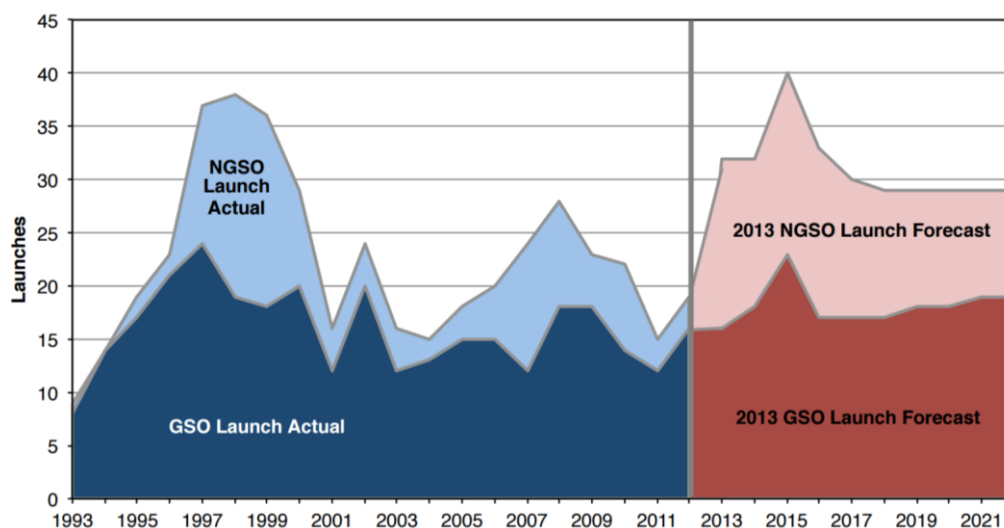


Figure 4: Combined 2013 GSO and NGSO Historical Launches and Launch Forecasts
(source: [9.])

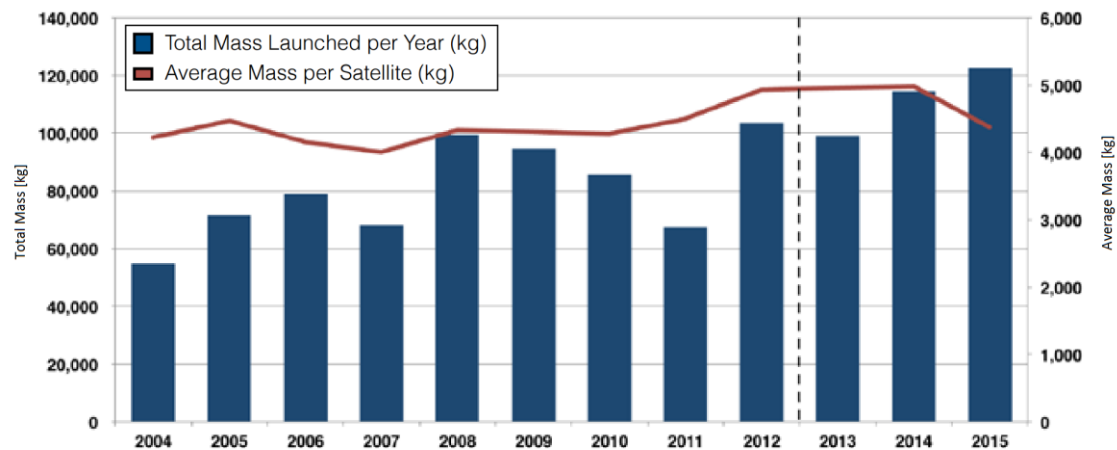


Figure 5: Total Satellite Mass Launched per Year and Average Mass per Satellite (source: [9.])

There are two approaches these hypersonic vehicles could follow. The first would be a more economic version of today's expendable launch vehicles. Developing vehicles, which can be reused after launching the payload to orbit, would significantly reduce the recurring cost of launches, as a new vehicle wouldn't be built for each mission. However this raises the question, whether a large and complex hypersonic vehicle, including the design and testing costs, would truly cost less than a very simple, less efficient, but inexpensive expendable launch vehicle. Furthermore, here is a trend these days to launch more, smaller and less complex thus cheaper objects into space. These objects could possibly be launched more economically with several smaller cheap launchers, than a single large reusable one requiring expensive orbital manoeuvres. Using reusable vehicles instead of expendable ones not only reduces manufacturing cost, but turnaround times as well. However maintenance has to be accounted for to determine commercial feasibility: the Space Shuttle required an army of 9000 people to maintain, refurbish and relaunch its fleet of 5 vehicles. 75% of maintenance involved the propulsion system and the heat shield: 20000 ceramic tiles required more than 17000 man hours after each flight [10.].

The alternative approach to hypersonic vehicles is to provide capabilities that do not yet exist, and would be impossible or very disadvantageous to achieve with expendable launch vehicles. These capabilities include responsiveness, quick turnaround time and operational flexibility. The USAF Operationally Responsive Space program is aiming to develop spacecraft and infrastructure which could achieve this goal. The USAF realised that currently both the military and civil sectors are highly dependent on orbital infrastructure (for example the GPS), and thus crippling a hostile nation's access to satellites while protecting their own, even replacing lost communications satellites at short notice could offer significant advantage, justifying the higher overall cost of a complex reusable launch vehicle. Also included in this category is the emerging sector of space tourism. Both governmental agencies (NASA [11.]) and commercial companies (Futron [12.]) produced market studies for space tourism, with optimistic forecasts of 16,000 suborbital passengers by 2020. NASA however predicts only 143 space tourist flights due to the current lack of crew transportation systems, the high cost involved and the current lack of destination other than the International Space Station. Historically in the first decade of 2000, only 8 space tourist flights were made. In addition to the launchers, transports can also provide capabilities, previously unavailable. These would be very similar to the hypersonic equivalent of the Concorde or Tu-144, both in terms of benefits and issues. These design issues related to the design of a supersonic vehicles were earlier summarised by Smith [13.]. Further regarding sub-orbital activity, the Tauri Group published an FAA funded report into sub-orbital reusable vehicles. Based on their survey, these vehicles can perform the following activities:

- Commercial human spaceflight
- Basic and applied research
- Aerospace technology test and demonstration
- Media and public relations
- Education

- Satellite deployment
- Remote sensing
- Point-to-point transportation

The estimated trends, assuming a conservative, baseline and optimistic scenario are shown in Figure 6. As it can be seen, even according to the constrained growth scenario, over 10 years (by 2022) the suborbital launch market is able to generate over \$300 million revenue, and has an optimistic potential of \$1.6 billion. For comparison, the total contribution of aviation in 2012 to the US GDP was \$847 billion (5.4% of total GDP), from which commercial airline operations contributed \$189.7 billion and general aviation operations \$20 billion. [14.]

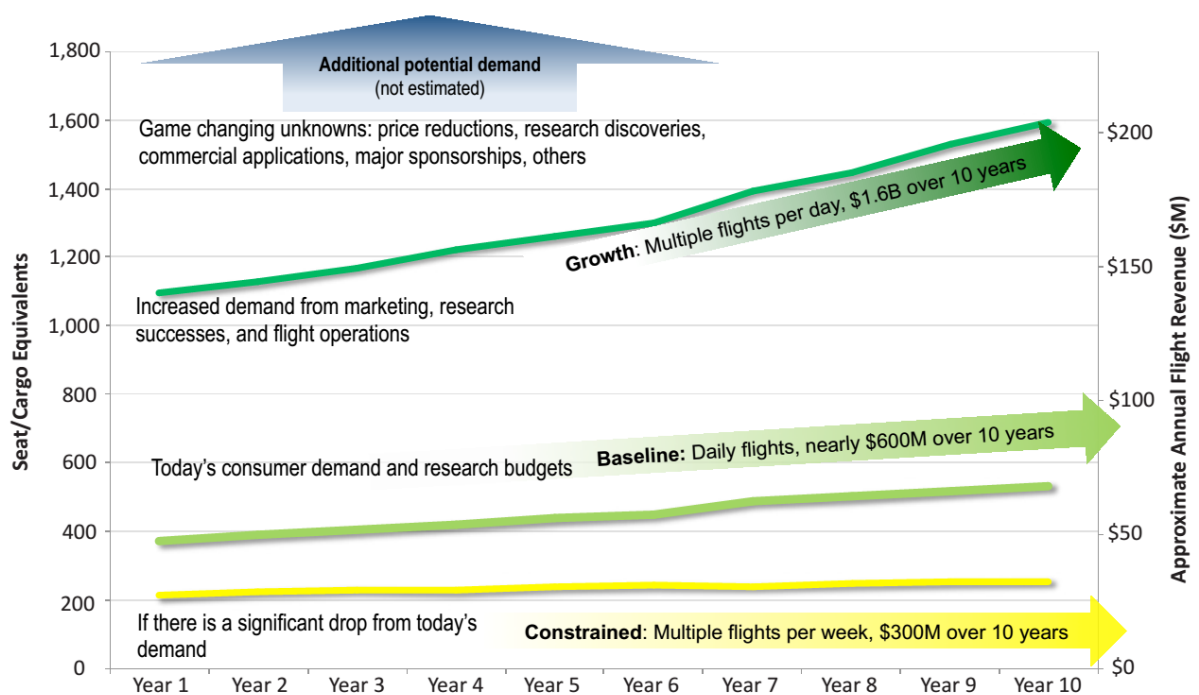


Figure 6: 10-year SRV demand forecast (source: [15.])

3.3 Environment

Due to the special nature of hypersonic flight, the very high level of technology involved, and especially its strategic value to the military, environmental concerns are usually less important than other aspects of the design. However the environmental issues not only concern local emissions (both pollutants and noise) by the aerospace vehicle, but also the effect on the global climate, the cabin environment, sustainability and sonic signatures.

3.3.1 Global Environment

According to the technical summary by Barker et al [16.] the aerospace sector contributes to 480 Mt/year CO₂ emission (2000), which is about 2% of all anthropogenic CO₂ emissions. Also along with the rest of the transport industry, they are responsible for small amounts of CH₄ and N₂O emissions from fuel combustion and fluorinated gases from air-conditioning. Although this percentage is low, considerable amount of these emitted pollutants are expelled at high altitudes, which can have amplified effect, even water vapour contributes to the greenhouse effect at high altitudes.

It has to be noted that the current space launch vehicles use different fuels and thus some of them emit additional pollutants. Liquid fuelled rockets mostly use cryogenic hydrogen and oxygen, which emit only water vapour, which have the aforementioned effect. There are many concepts for hydrocarbon based or tri-propellant liquid rockets, for which emissions are somewhere between that of pure hydrogen and pure hydrocarbon based propulsion. Solid fuels however, in addition to the fuel and oxidizer, include additional components, such as fine aluminium powder to increase the specific impulse of the propulsion system, bonding and stabilizing agents, etc. These additives, either in burnt or unburnt forms have further adverse effects on the global environment.

Due to the initial low number of hypersonic vehicles they are estimated to contribute only a minor part in the emissions at a global scale.

3.3.2 Local Environment

The effect of a hypersonic vehicle on the local environment depends significantly on the launch and landing method the vehicle utilises and also on the fuel used. As there are many approaches, each will be briefly discussed.

The “classical rocket” launch method or vertical take-off is almost exclusively used for today’s launches, except for a small amount of air launched vehicles. This method places demanding requirements on the launch site: from the point of engine ignition throughout the lift-off and the following few seconds, the powerplants are utilizing maximum power, producing tons of exhaust gases per second. In addition to the gases, solid particles such as black carbon (soot) are also expelled from the engine (in the case of hydrocarbon fuels). These particles, in addition to their climate changing roles at higher altitudes, are also carcinogenic, posing a possible health hazard to humans. The final emission type, which is of great concern during a vertical launch, is the acoustic emission. Due to the considerable power of the engines, some sound damping medium must be used to prevent damage to the spacecraft, the launch site or, the often sensitive payload. This is normally done by injecting large masses of water into the exhaust of the rocket. However even with such a mitigating step, the launch site must be located in an uninhabited area to prevent human injury and damage to property. The large volume of water used could also have detrimental effects on the local environment.

The other method, the horizontal launch, is utilised every day by aircraft across the globe. Aerodynamic lift on aircraft usually requires less thrust than a comparable vertical rocket launch due to their glide ratio or L/D ratio. A modern airliner such as the B737 or A320 has an L/D of about 16, while a more blunt shape, such as the Space Shuttle, is about 4.5. Lifting bodies can be just marginally over 1. When relying on aerodynamic lift to sustain flight, a vehicle only has to produce thrust force equivalent to its drag. As L/D values for these vehicles are in excess of 1, it can be seen that less thrust is required when relying on aerodynamic lift than when the vehicle’s whole weight is supported as

thrust force, as in the case of vertical take-off vehicles. Furthermore, as the exhaust is not confined to the space under the vehicle as in vertical launch mode, the acoustic emissions would be less problematic and it would be more akin to a large commercial airliner. Concepts such as aerial refuelling and two or more stage to orbit vehicles deal with the emission issues by igniting the main engines at an altitude after refuelling or separation (respectively). This would enable the vehicle to produce emission levels that would be unacceptable at ground level.

As far as landing is concerned, winged vehicles are able to fly or glide to selected airports (spaceports), while vertical landing vehicles have to fire retrorockets before landing, which have a similar effect to take-off but, due to the much lower landing weight, not as powerful. Alternatively the vehicles can land using parachutes, and/or splashdown in water. The vehicles' cross-range characteristic is an important measure, showing what range the vehicle can cover after re-entering the atmosphere. Due to the uncertainties in trajectory and atmospheric properties at re-entry, instead of a single point, the vehicle is allocated a re-entry window. Based on this window, and its cross-range characteristic, a re-entry area is calculated, and appropriate landing sites can be selected.

More exotic concepts such as sea, magrail or gas gun launch have their advantages but the changes in emission characteristics are usually of lower priority.

3.3.3 Cabin Environment

For a hypersonic vehicle it is of paramount importance that the structural mass is minimised, as this has a snowballing effect on the fuel required and greatly affects the overall mass of the vehicle. As a result, producing a vehicle with cabin pressures and temperatures where no additional protective equipment is needed to survive (also known as a "shirt-sleeve environment") needs a very good reason to justify the additional mass added to the vehicle. This increase is due the additional structural mass to sustain pressurization and extra air conditioning/life support systems mass. Depending on the

application this might be justified, for example a vehicle designed for long duration space tourism, while a military spacecraft is more likely to utilize protective suits for the crew or passengers. It is also questionable, whether the vehicle needs a crew at all (see the autonomous flight of Buran or X-37 for an argument supporting this choice). Choosing a human rated vehicle poses multiple constraints: the maximum continuous acceleration has to be limited (usually to 3g [17.]), which requires a variable rocket throttle resulting in a more complex propulsion system. Also the crew and passengers, and sensitive equipment must be insulated from both the heat and vibration of the propulsion systems, direct sunlight, re-entry, and the cold of the upper atmosphere or space. In addition to this, increased reliability and abort capability is required. For full list of NASA's human rating procedures, refer to NPR 8705.2B [18.].

Another source of hazard to humans, which must be mitigated, is the increased amount of radiation. While some part of this can be anticipated, and thus avoided such as the Van Allen belt, there are others which occur fairly randomly such as solar wind and cosmic rays. To protect against this latter category, the vehicle must have adequate absorption capability built into the walls, either as exotic structural materials or additional layers (materials with high hydrogen concentration such as polyethylene or water), both of which increase structural mass and volume resulting in a higher overall all-up-mass. The radiation intensity will increase with altitude, so a sub-orbital hypersonic transport would require less protection than a vehicle designed for space use. The current recommended maximum radiation rate for aircrew by the FAA (and the EU) [19.] is an average of 20mSv per year on a five year average, not exceeding 50mSv in any single year. Comparatively, a short-haul flight results in 1-3 μ Sv per hour, while a supersonic high altitude cruise such as the Concorde reached up to 12 – 15 μ Sv per hour. According to NASA, the exposure limits for astronauts are 50 rem annually [20.] (1 rem is equivalent to 0.01 Sv), with a limit to 25 rem per 30 days. It can be seen, that this amount is 25

times higher than the limits and, as such, requires mitigating steps if hypersonic high-altitude flight is to become as widespread as today's airliners.

Another aspect of the cabin environment is the pressurisation. The Space Shuttle was designed to maintain a nominal cabin pressure of 14.7 psi (1 bar sea level pressure), or a minimum of 8 psi in case of emergencies. It has to be noted that before EVA, the cabin pressure was decreased to 10.2 psi, to reduce the risk of decompression sickness. [21.] Space suits on board the Space Shuttle (EMUs) operated at 4.3 psi (30 kPa), the advanced EMU at 8 psi (55 kPa) [22.], while the Russian Orlan space suit at 5.8 psi (40 kPa) [23.]. The International space station also maintains a sea level pressure on board [24.]. Depending on the mission of the Space Launcher, this pressure could be lowered, although the effect of long exposure to low pressure on the crew's health must be borne in mind. Generally, people suffer from hypoxia at (pressure) altitudes of 4500 m and over when breathing in air; for comfortable breathing a maximum pressure altitude of about 2500 m is ideal. It is possible to breathe in oxygen enriched air up to 13km pressure altitude, but above that altitude, even in pure oxygen environments, it is impossible for the human body to absorb enough oxygen. A compromise has to be found between comfortable environment and the structural stresses and fatigue issues introduced by a higher cabin pressure.

Astronauts on board the ISS suffer from muscle and bone mass loss during the mission duration, as all the muscles that have to constantly work and resist gravity on Earth are not stimulated in weightlessness. Furthermore, as the absorption of calcium into the skeleton requires vitamin D, which requires exposure to natural sunlight, calcium absorption levels are lower in space [25.]. Rigorous training regimes and vitamin supplements are used on board the station to minimize this effect and keep the astronauts in good health. As a general rule the combined muscle and bone mass loss is about 1% for every month spent in space, thus it is unlikely that this is going to be a

major issue for a Space Launcher, however missions with extremely long durations will have to take this into account.

3.3.4 Sustainability

Since hypersonic flight is still at a low technology readiness level, sustainability is usually of secondary priority, which could be studied in more depth once vehicles are operating. On the other hand, a vehicle designed with sustainability in mind would be desirable from the outset to lower the environmental impact of the hypersonic industry.

An area where sustainability must be considered carefully, is the choice of propellant. Today's high speed aircraft and rockets utilise either hydrocarbon-based fuels (mainly kerosene), cryogenic hydrogen and oxygen, or solid fuel. The detrimental effects of these propellants are well known, but accepted by today's society. Fossil based hydrocarbon fuels have a limited predicted availability, and seem to be a less clean energy source than hydrogen and oxygen. There have been many experiments with different fuels, such as Boron-gel high density fuel or Methycyclohexane. The problem with these is that the exhaust products are highly toxic, and thus they do not offer a sustainable alternative for large scale use as compared to fuels with more benign emissions such as hydrogen.

An additional aspect is the manufacturing and maintenance of the vehicles. Being such high-technology systems, it is very likely, that they would incorporate exotic, complicated to manufacture, and in some case environmentally unfriendly components and fabrication methods, such as composites or block machined alloy parts. End of lifecycle issues also occur, as safe disposal or recycling of composites is still not a fully developed process. Also many parts are potentially contaminated or plated with environmentally hostile materials, such as cadmium. This seems to be inevitable at this stage, perhaps with further improvements in material, manufacturing and recycling technology and considerably more experience, they could be mitigated.

3.3.5 Sonic signatures

The current practice of launching spacecraft utilises strict range safety rules to prevent any damage to the surrounding population and objects. For this reason, the launch locations are usually chosen at remote locations, either near the ocean or sea, or in an uninhabited area. To date there has been no damage associated with the launch or re-entry of space objects due to these range safety requirements and careful planning.

Launching from a remote location also means, that the issues associated with the sonic-boom are less of a concern than, for example, a civil airliner. However, enabling future hypersonic vehicles to fly over populated areas would give considerable operational benefits, resulting in large scale economic improvements.

At the dawn of supersonic flight, the allowed maximum overpressure was limited to 2 pounds per square foot for climb, and 1.5 pounds per square foot for cruise [26.]. For more recent vehicles, according to the NASA Dryden Flight Research Center publication, the following overpressures were measured at supersonic speeds:

Table 2: Supersonic sonic overpressures

| Aerospace vehicle | Mach number [-] | Altitude [ft] | Overpressure [lb/ft ²] |
|-------------------------------------|-----------------|---------------|------------------------------------|
| SR-71 | 3 | 80,000 | 0.9 |
| Concorde | 2 | 52,000 | 1.94 |
| F-104 | 1.93 | 48,000 | 0.8 |
| Space Shuttle (landing approach) | 1.5 | 60,000 | 1.25 |

Public reaction can be expected from overpressures of 1.5-2 pounds per square foot, while values in the range of 2-5 would cause minor damage to structures on the ground, depending on the structural state of the structure. It also has to be noted, that the data in Table 2 are valid only for cruise. Manoeuvres or unevenness in the ground could

result in a significant increase of this overpressure. Seasonal changes in the Earth's atmosphere also have an effect on the perceived sonic boom.

A hypersonic vehicle, such as the Apollo 15 at re-entry (Mach 15.62) generates an overpressure of 0.223 psf, which is significantly less than that of the supersonic vehicle data. This is mainly due to the altitude at which the spacecraft was flying. Figure 7 shows a comparison between wind tunnel measurements and measured data at a condition of M 4.57 at 110,304 ft during re-entry. It can be seen, that the maximum overpressure measured was as low as 0.418 psf.

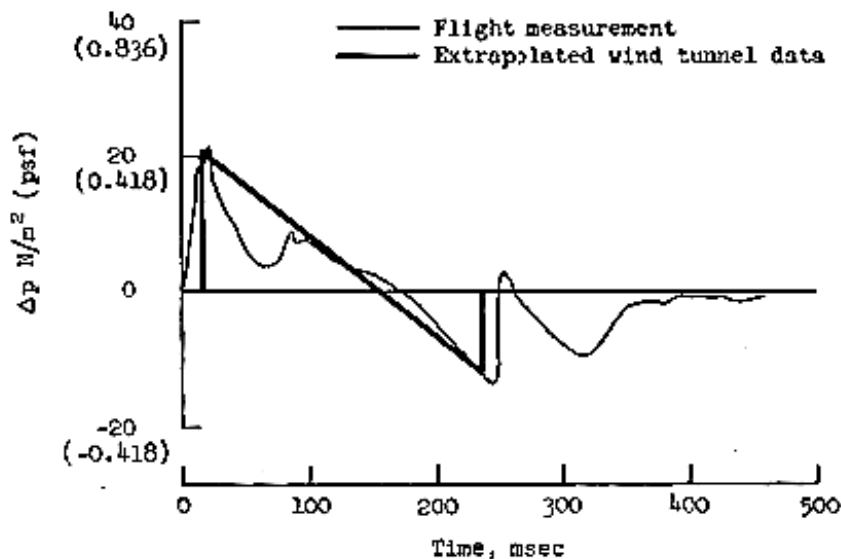


Figure 7: Overpressure characteristic of Apollo 15 re-entry (source [27.]

Similar measurements were made for the Apollo 16 re-entry, where a maximum overpressure of 0.418 psf was measured at M 9.71 (and reproduced in the wind tunnel). In the case of Apollo 16, overpressure values were measured during launch as well, ranging from 0.87 to 2.8 psf [28.], although it has to be noted that the high values are mostly due to the large rocket exhaust plume and the ground-focus effects, and as such are characteristics of a vertical take-off vehicle. This overpressure can cause damage to buildings in poor structural condition, but poses no health risk to humans.

Several measurements were made for the Space Shuttle missions, beginning with STS-1 on 12 April 1981, a total of 26 flights were documented. During take-off values between 0.4 psf (pre- and post-focus region) and 6.81 psf (focus region) were measured, while during re-entry 0.1 psf (243,000 ft) to 2.32 (ground level) were obtained. [29.]

Estimations were made for the sonic boom signature of massive objects such as the Mir space station during re-entry (M 24.79). According to simulations the near-field pressure increase was 6.54 psf, with an estimated 0.183 psf pressure rise for each individual module after breaking up in the atmosphere. Unfortunately no measurements could be made during re-entry, the only resource is a descriptive definition by CNN cameraman Hugh Williams [30.].

As a conclusion it can be said, that the sonic boom signature of a hypersonic vehicle is more critical at lower Mach numbers and altitudes, but not significantly different from a large supersonic aircraft, and as such the steps to mitigate the negative effects could be similar. As an added benefit, due to range safety, current launch sites and spaceports are situated in remote areas, where the sonic signature is less concerning.

4.0 Technological issues

4.1 Aerodynamics

One of the greatest concerns with a hypersonic vehicle is the aerodynamic performance. Due to the extensive range of speeds the operational envelope covers, the designs have to fulfil several, often contradictory requirements. The main focus, however, is the reduction of drag during the ascent phase (and cruise for transports). Figure 8 shows a comparison between various aerospace vehicles' maximum flight speed.

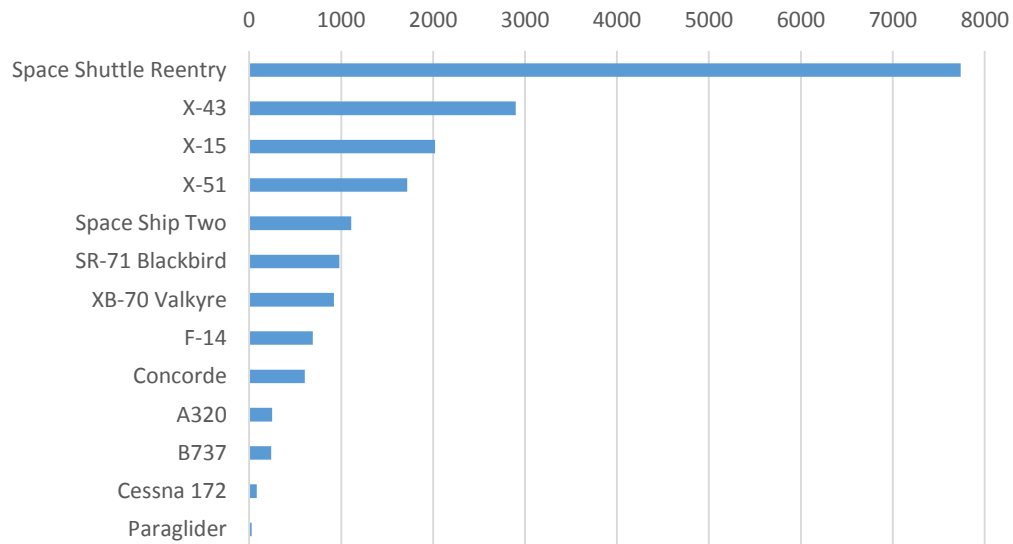


Figure 8: Typical maximum flight speeds for various vehicles, TAS [m/s]

4.1.1 Aerodynamic lift

Unlike conventional aircraft, where the lift has to balance the weight to sustain flight, a hypersonic vehicle can rely solely on thrust, provided the engines are powerful enough. Thus the importance of aerodynamic lift depends on the actual vehicle configuration. Non-lifting (ballistic) vehicles don't rely on aerodynamic lift, which result in sleeker, lower drag shapes, but their cross range capability and controllability are poor. High hypersonic lift, however results in higher deceleration at higher altitudes, which reduces the peak heat, and overall maximum deceleration loads on the vehicle. Also lift can be used to provide safe launch abort capabilities. In the case of a horizontal take-off vehicle, it is essential to provide large amounts of lift, as it is required during the take-off and climb phase. Utilising aerodynamic lift reduces the thrust required compared to lifting the vehicle vertically, but this mainly depends on the lift to drag ratio of the vehicle. Refer to Table 4 for typical L/D ratios.

The lift characteristics of hypersonic aircraft are fundamentally different from subsonic or linearized supersonic behaviour. The methods used to evaluate hypersonic aerodynamics depend on the vehicle shape.

For blunt shapes such as the flat underside of the Space Shuttle or similar vehicles, hypersonic aerodynamics can be approximated using the Newtonian flow theory. This theory models the flow as many small individual particles, impacting a surface, losing their normal, but retaining the tangential speed components. Investigating the behaviour of a flat plate shows remarkable similarity with the usual lifting surfaces, and thus understanding it gives insight into the fundamental behaviour of hypersonic lift.

Using the Newtonian sine-squared law, the lift and drag coefficient of a flat plate can be derived as:

$$c_l = 2 \cdot \sin^2 \alpha \cdot \cos \alpha \quad (1)$$

$$c_d = 2 \cdot \sin^3 \alpha \quad (2)$$

Neglecting friction, it can be seen in Figure 9, that the theoretical lift curve at hypersonic speeds follows a non-linear behaviour, reaching its maximum at 54.7° . Unlike subsonic flows, where the peak is followed by a stall region, and the loss of lift is due to separation of the flow, here it is due to the behaviour of the trigonometric functions.

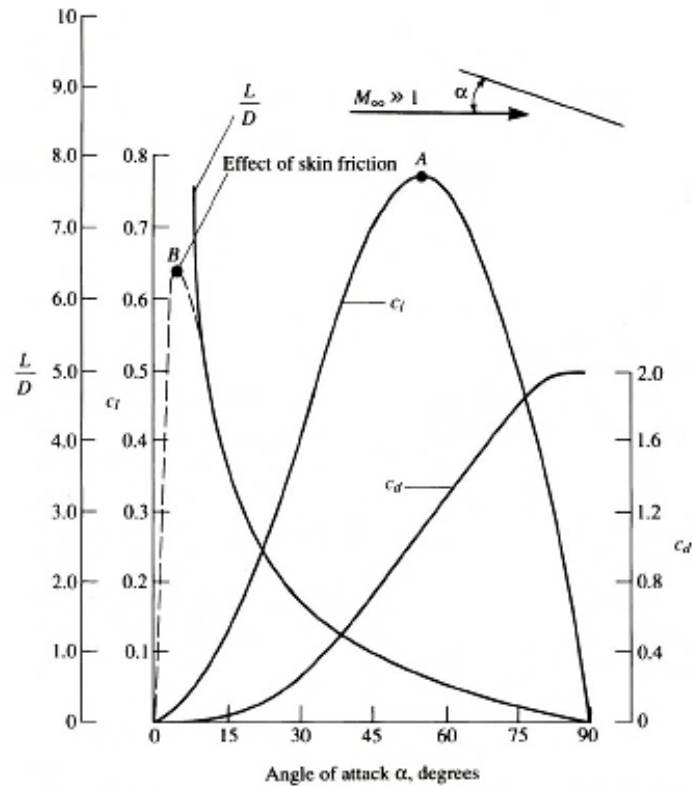


Figure 9: Lift and drag characteristics of flat plate in hypersonic flow (source [31].)

The Newtonian theory simplifies the flow from two important points of view. First, it ignores any cross-flows or pressure effects and approximates aerodynamic loads solely based on geometric angles. The other very important simplification, and limitation, is that it does not treat the flow over the “shadowed” side of the vehicle. This is appropriate for a flat plate, where there is essentially ambient pressure over most of the leeward side, but it introduces significant errors for example in the case of diamond shaped aerofoils used on Hypersonic Transports, where expansion effects need to be taken into account. One method such as this is the Shock-Expansion method, where only the principal characteristics of the flow through shockwaves derived from three dimensional characteristics theory are considered, and other secondary effects such as reflections from the shockwave and vortex lines are ignored. The method was introduced in 1931 by Epstein [31.].

There were many other methods developed over the years to address flows around different geometries. There is no single method universally applicable to any vehicle shape, the designer needs to have good understanding of the fundamentals and underlying assumptions of the various methods. Table 3 shows a list of various compression and expansion methods used to estimate hypersonic aerodynamic performance. These methods form part of the SHABP software and for more details on the methods, their applicability and implementation as computer code, one should refer to the Program Formulation manual [32.] and Dirkx and Mooij for modelling methods and comparison with real vehicle flight data [33.].

Table 3: Compression and expansion methods used for hypersonic flows

| Compression methods | Expansion methods |
|-----------------------------|----------------------------------|
| Modified Newtonian | $C_p = 0$ |
| Newtonian-Prandtl-Meyer | Newtonian-Prandtl-Meyer |
| Tangent Wedge | Prandtl-Meyer |
| Tangent Wedge Infinite Mach | Cone At Angle Of Attack |
| Old Tangent Cone | VanDyke Unified |
| Cone At Angle Of Attack | Vacuum |
| VanDyke Unified | Shock Expansion |
| Blunt Body Viscous | Input Value |
| Shock Expansion | Free Molecular Flow |
| Free Molecular Flow | Modified Dahlem-Buck |
| Input value of C_{pStag} | ACM empirical |
| Hankey Flat Surface | Half Pradt-Meyer from freestream |
| Smyth Delta Wing | |
| Modified Dahlem-Buck | |
| BlastWave | |
| OSUBluntBody | |
| Tangent Cone (Edwards) | |

Those aircraft, which are utilising lift for ascent fall into either the winged or lifting body category. The winged configuration offers a higher lift to drag ratio at subsonic speeds, but increases structural mass and drag compared to the lifting body. At hypersonic

speeds wings are disadvantageous, as long thin surfaces are not efficient structures, thus they have to be heavy to survive re-entry loads. The table below shows some winged and lifting body vehicles with their respective L/D ratios. According to NASA investigations [35.], the theoretical maximum hypersonic lift-to-drag ratio (with a skin-friction coefficient of 10^{-3}) for a conventional low-winged configuration, such as the Space Shuttle, is 5.29. However, a flat-top, high wing type configuration, X-43 for example, could reach up to 6.65 L/D at Mach 5 [36.]. Although, due to aerodynamic heating issues, the low wing vehicles, such as the X-20 Dyna-soar, were chosen as the first designs to develop [37.].



Figure 10: Low and high wing hypersonic shape comparison: Space Shuttle (left) X-43 (right) (source: [38.])

Table 4: Lift to drag ratio comparison [39.] [40.] [41.] [42.] [43.]

| Vehicle | Lift to drag subsonic | Lift to drag supersonic | Lift to drag hypersonic |
|----------------------------|-----------------------|-------------------------|-------------------------|
| Space Shuttle | 4.5 | 2 | 1.5 |
| Buran | 5.0 | No Data | 1.7 |
| X-15 | 4 | 2.5 | 2.5 |
| X-20 | 4.3 | No Data | 1.5-1.9 |
| Common Aero Vehicle (X-41) | No Data | 2.5 | 3.5 |
| SpaceShipTwo | 7 | 0.5 | Not Applicable |

There is a special class of lifting body aerospace vehicles called the waverider. This is a specially designed vehicle that utilises its own shockwave to generate extra lift to improve its lift to drag ratio. The concept was developed by Terence Nonweiler. [44.] Up to day, only the Boeing X-51 has actually demonstrated flight with this shape. The drawback of

the waverider is that it can only achieve the lift increase at a specific Mach number and altitude combination, to which the geometry was optimised. There is no drawback to a waverider design compared to a conventional lifting body vehicle. The shock wave when positioned correctly could also provide ram compression for airbreathing powerplants.

4.1.2 Aerodynamic drag

It is important to understand that unlike airliners, where there is a significant component of lift induced drag, the drag of a spacecraft comprises mostly of base and wave drag, and so it depends more on the volume and cross-sectional area of the vehicle, than the mass. This is important, as it means that the payload carried by the vehicle must have strict volume limits in addition to mass limits. Furthermore, this means that some fuel types, especially liquid hydrogen and other low energy to mass ratio fuels could be disadvantageous despite their high specific impulse and good emission characteristics.

As one of the main parameters of a launcher is the total change in speed or Δv it can achieve by burning all the fuel on board, the aerodynamic drag is often represented as a Δv increment in addition to that required to reach a specific orbit. The atmospheric drag is often combined with the gravity drag to give a total Δv increase. Gravity drag results from the fact that in addition to accelerating the spacecraft, we also have to resist the gravitational pull of Earth. As such gaining altitude and reaching the orbital speed as soon as possible is a preferred way to reduce these two drag components. From this respect a vertical launch vehicle seems more efficient than a horizontal take-off, because the flight path angle and acceleration is high, to leave the atmosphere in the shortest possible time, thus minimising gravity drag. This shows that the horizontal take-off configuration is only efficient if the lift to drag ratio is sufficiently high, to compensate for the additional time spent during the climb phase, and as such the increased gravity and aerodynamic drag losses compared to a vertical take-off vehicle. For a typical rocket launched to LEO, the atmospheric and gravity drag adds up to about 1.5-2 km/s Δv increment, compared to the 7.8 km/s baseline as calculated from the Tsiolkovsky rocket

equation. It has also to be noted, that the aerodynamic drag losses account for up to around 10% of the total Δv increment, and as such the gravitational losses are the dominant component. [45.]

In the case of a hypersonic transport, the issues with aerodynamic and gravity drag are not significantly different from the launcher vehicle, as a transport would also have to reach high altitudes to enable the hypersonic cruise.

The key question here is whether it is better to follow a lifting trajectory or to ascend like a rocket. The benefits of lifting flight is that the vehicle can capitalize on the reduced thrust requirements due to the L/D ratio larger than unity, thus enabling the propulsion systems to be potentially significantly smaller. The propulsion system usually contributes to significant percentage of the vehicle's empty mass, thus the lower the empty mass to launch, the less fuel is required, which allows smaller structure, and so on, this can have a snowballing reduction effect on the total mass. Also, in the case of many concepts, the propulsion systems pose a minimum diameter constraint on the vehicle size. Reducing the required thrust reduces the propulsion system size, and enables the design of sleeker, lower drag configurations.

Lifting ascent on the other hand, comes with disadvantages as well. First of all, a lifting structure is required, which adds considerable mass to the structure. As the wings are not solely used during ascent, but at approach, landing and most importantly re-entry as well, where they are most beneficial to reduce heat fluxes, thus potentially TPS mass, this added mass can be justified, or even negated with other mass savings.

Where the lifting ascent falls behind a rocket type vehicle is the losses due to the chosen trajectory. The ultimate aim of these vehicles, both Space Launchers and Hypersonic Transports is to climb to a high altitude, and acquire high velocities. It can be seen, that the fastest way to achieve this is with a near vertical climb at maximum acceleration, which is exactly the rocket type ascent. When the vehicle starts to rely on aerodynamic

lift to support its weight, it will reduce the required thrust, but must do so by also reducing flight path angles, no longer achieving the near vertical climb trajectories. When the flight path angle is reduced, it can be seen, that to climb to the same altitude would take longer than in the case of the vertical ascent. This additional time spent in the atmosphere is the source of their major disadvantage. The fuel used to reach the given altitudes is proportional to the product of the power used by the system and the time it takes to reach the given altitude. In many cases the reduction in the power required due to aerodynamic lift is significantly lower than the additional time required to climb, thus suggesting that the rocket type ascent is superior in many cases. However this has to be evaluated on a concept-by-concept basis, as the factors affecting these are many; mainly L/D ratio, propulsion system performance, fuel types, trajectories, all evaluated over the full speed and altitude range and with possible different control strategies, for example in the case where multiple propulsion systems are installed on the same vehicle. This is indeed one of the main challenges of hypersonic vehicle conceptual design.




4.1.3 Stability and control

Designing stability and control characteristics for a hypersonic vehicle is not an easy task, and the reason for it is twofold: first, the vehicle operates at a wide range of speeds and also distinctly different environments.

The effects of the wide speed range mainly concerns the change in lift distribution, and thus the position of the aerodynamic centre, the change of effectiveness in control authority of the control surfaces and the aeroelasticity effects. When the aerospace vehicle accelerates from subsonic to supersonic speeds, the aerodynamic centre travels rearwards, thus altering the static margin and the stability characteristics.

EFFECT OF ASPECT RATIO AND SWEEP

$$\Delta \bar{x} = \bar{x}_M - \bar{x}_{M=0.25}; \lambda = 0$$

| EXP | WING-ALONE THEORY | A | Λ , DEG | |
|-----|----------------------|---|-----------------|--|
| ○ | — | 2 | 63.5 |  |
| □ | - - - | 3 | 53 |  |
| ◇ | — | 4 | 45 |  |

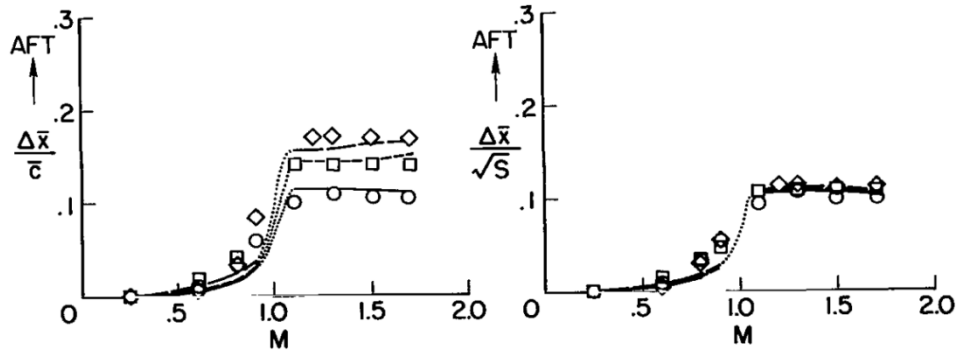


Figure 11: Aerodynamic centre position with changing Mach number for various aspect ratio and sweep (source: [46.]

To maintain the stability characteristics over the speed range, there are some options available. Aerodynamic surfaces can be employed, which can produce changes in the overall pitching moment slope, such as in the case of F111, variable sweep wings. Additionally, centre of gravity shift can be employed, by pumping fuel to trim tanks, such as on the Concorde, shown in Figure 12.

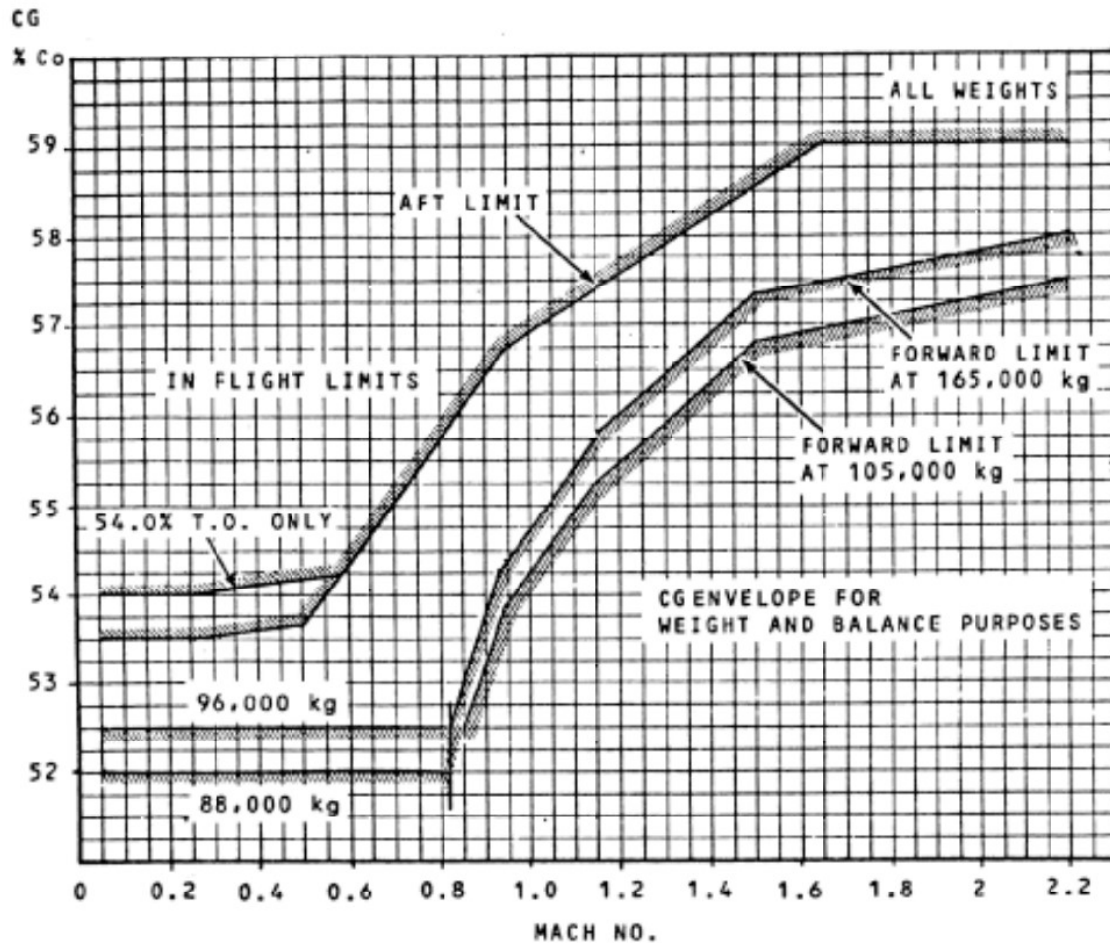


Figure 12: Concorde CG limit variation with Mach number (source: [47.])

Maintaining the stability margins is a delicate problem for hypersonic vehicles, as the large engines required to produce the large amount of thrust are usually mounted in the back, resulting in an aft CG position, which often results in trim and stability problems. Furthermore, the significant change in fuel quantity (over 90% of total mass) also shifts the CG (usually backward towards the heavy engines), further complicating the issue. The best example for this is the case of the HOTOL and Skylon vehicles, where the original stability problems with the HOTOL were mitigated by placing the engines at the wing tip, instead of the rear of the spacecraft. [48.]

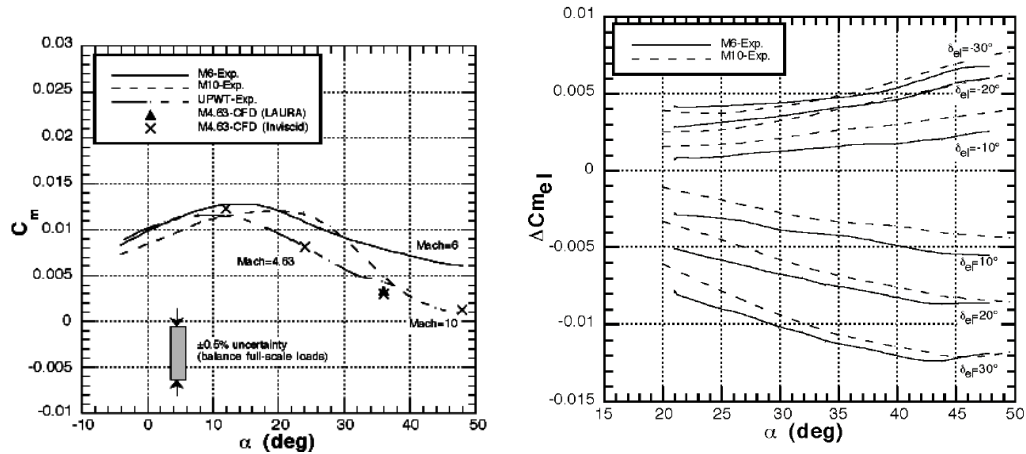


Figure 13: X-33 pitching moment and elevon authority as a function of AOA and Mach number (source: [49.])

As it can be seen in Figure 13, the authority of the control surfaces generally tends to drop as the Mach number increases, which makes the control of the aircraft at high speeds increasingly difficult. Sometimes however, as it can be seen at negative deflection angles, the efficiency of the control can improve. While the actual effect of Mach number change to the controls has to be evaluated for quantification, the change in effectiveness must be expected at every stage of the design nevertheless. Also, the second of the two issues mentioned, with increasing altitude, density reduces thus aerodynamic surfaces become progressively less effective. To counter this problem, most of the vehicles are installed with a reaction control system, which not only augments the control power at high speeds, but also enables attitude corrections outside the atmosphere. The available RCS propellants can be cold gas, fuel and oxidizer ignited or hypergolic fuels. On small spacecraft reaction control systems are usually operated by releasing inert gases such as nitrogen or helium or other gases such as methane. Larger vehicles, such as the X-15, use hydrogen-peroxide [50.] while some proposed configurations, such as the HL-42, burn liquid methane with oxygen in the reaction control systems. The Space Shuttle uses Monomethyl Hydrazine and Nitrogen Tetroxide RCS system [51.]. The drawbacks of using an RCS is the added weight and complexity for the system as a whole. RCS systems comprise nozzles, control valves, fuel tanks

(with fuel), insulation, structural supports, which all add to the overall mass, complexity. The Space Shuttle has 12800 kg of propellant on board (shared between the OMS and RCS) and the RCS system total mass is 1276 kg [52.].

Aeroelasticity and general structural deformations are also of great interest, due to the high performance requirements, and the many unknowns in hypersonic aerodynamics, the aircraft must operate close to the design point in order to maintain controlled, efficient and safe flight. This means, that the structural deformations allowed tend to be smaller than for a subsonic vehicle. The problem is further complicated by the addition of thermal effects due to friction. These aero-thermo-elasticity calculations still pose a great challenge to engineers and usually require considerable computational power to solve. Also, for some vehicles, specifically the Space Shuttle or the Buran, the heat shield for atmospheric re-entry is made of ceramic material, and the elastic behaviour of the vehicle is the reason for the 24,300 separate tiles used on the Shuttle, contributing towards the extremely high maintenance costs.

4.2 Propulsion

A second very important aspect of hypersonic flight, closely connected to aerodynamics, is the propulsion. It is probably the most critical factor that limits efficient and routine space access. The choice of propulsion for an aerospace vehicle is either the jet or rocket engine, as these offer the required performance for high speed flight. The most important characteristic of a propulsion system is the specific impulse. It is a measure of efficiency for the propulsion, the ratio of thrust generated divided by the flow of fuel (fuel flow can be either in weight flow [N/s] or mass flow [kg/s]). If the weight/sec definition is considered so the dimension is [s], it could be best described as the amount of time, that 1kg of fuel can provide 1 N of thrust. When dividing by mass flow, the dimension of specific impulse will be [N·s/kg]. Whichever unit is chosen, as per the definition, the higher the specific impulse, the more efficient the engine is. Figure 14 shows a comparison of the specific impulse of various propulsion systems as a function of Mach number.

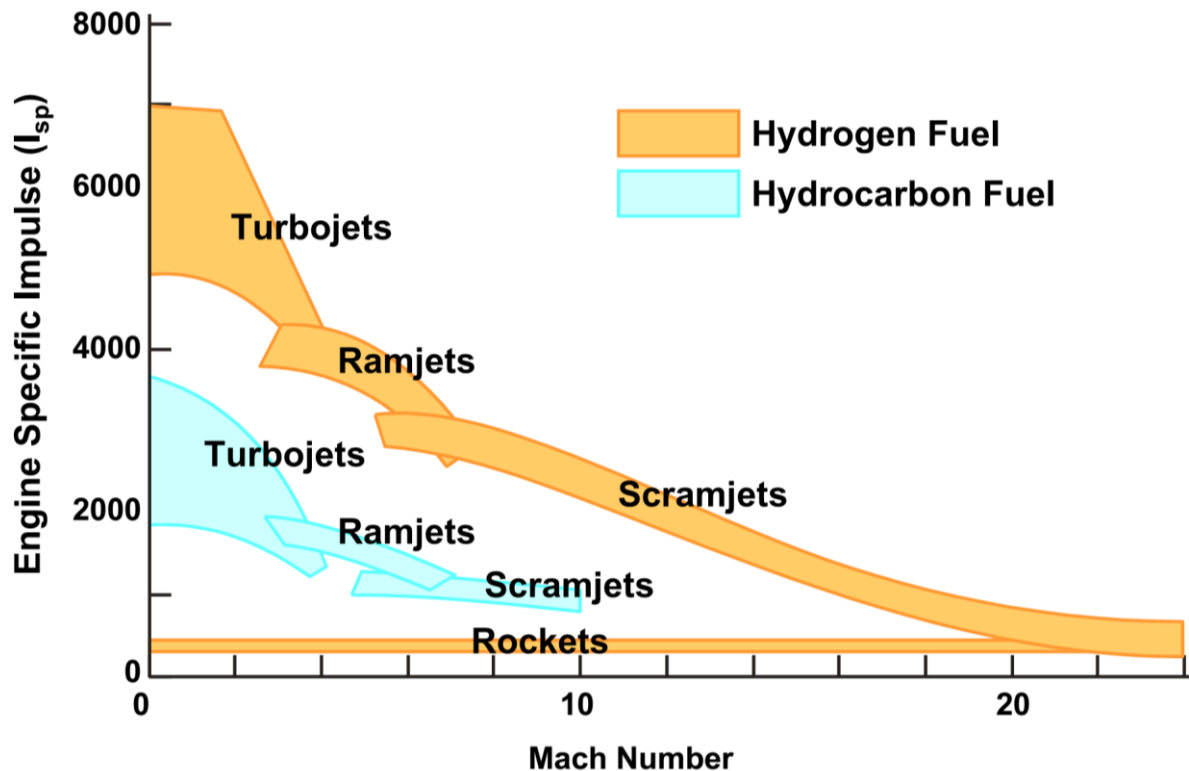


Figure 14: Hydrogen and hydrocarbon fuel propulsion systems comparison [53.]

It can be seen, that although rockets provide thrust throughout the whole Mach number range, their specific impulse is lower compared to the airbreathing engines. The explanation for this comes from the operational principles, as the airbreathers utilise the reaction force of large amounts of air propelled backwards, while only consuming a small amount of fuel. For a rocket engine all the reaction mass has to be carried on board and expelled, thus the small ratio. It can also be seen, that Hydrogen fuel provides a higher specific impulse for a rocket than hydrocarbon fuels.

In addition to the specific impulse, another very important aspect of rocket engines is the available thrust. Having high specific impulse doesn't mean that the propulsion system is also capable of providing high thrust. For example, a propulsion system with a very high specific impulse is the ion-propulsion utilised for spacecraft. Their specific impulse is in the magnitude of 6000-10000 s, some claiming even 20000s but the thrust provided is in the 0.05-3 N range. This means, that they are very efficient means to accelerate a

spacecraft over long period of time, but they are unable to produce the required thrust to lift-off from the ground or even manoeuvre. As a comparison, the Rolls-Royce/Snecma Olympus engines powering the Concorde had an I_{sp} of 3000, and a (wet) maximum thrust of 169 kN.

4.2.1 A list of propulsion systems

1.1.1.1 Airbreathers

- Turbojet: Turbojets offer the highest specific impulse due to the large amount of air moved. While pure turbojets offer the highest thrust, turbofans offer a higher efficiency. Military supersonic aircraft are usually powered by low bypass ratio turbofans with afterburners. These systems can be used to take-off and propel the vehicle to low supersonic speeds. Due to high dynamic pressures, unducted configurations, such as turboprop or propfan are not promising choices for a hypersonic vehicle.
- Ramjet: A ramjet utilises the high speed of the aircraft to compress the air at the inlet of the engine, and as such do not require rotating compressor or turbine parts, greatly reducing the complexity compared to a conventional jet. However due to the way compression occurs, they are incapable of providing thrust at low Mach numbers, and they also have an upper limit around M 5.5. One of the definitions of hypersonic speeds is the limit, where ramjets stop generating thrust.
- Scramjet: Scramjet is an abbreviation of supersonic combustion ramjet. The working principle is the same as a ramjet, but the combustion occurs at supersonic speeds, which enables the engine to operate above the Mach limit of normal Ramjets. Scramjet engines are still under development, some aircraft successfully flown with scramjets are the US X-43 Hyper-X [54.], X-51 [55.], the Russian AJAX [56.], and the Australian HyShot [57.] test aircraft.

1.1.1.2 *Rocket based*

- Rocket: The rocket carries both fuel and oxidiser on board, so it doesn't rely on atmospheric oxygen, which enables it to operate outside the atmosphere. They produce a constant amount of specific impulse, but their thrust depends on altitude because the exhaust nozzle is optimised to one expansion ratio and thus one altitude. Usually adaptable nozzles induce additional weight and complexity which does not justify the performance gained. Another subtype of rockets with altitude compensating nozzles is the aerospike engine [58.]. These use an inverted approach to bell nozzles, and such use a spike at the centre of flow and the atmospheric air as the outer boundary of the exhaust plume. They were proposed for the X-33 and Venture Star designs but as of today there are no aerospike engines in operation.

1.1.1.3 *Hybrid/combined cycles*

- Air augmented/ducted rocket: Their working principle is somewhat akin to the turbofan concept. They utilise an additional duct around the main rocket, which collects ram air, and the exhaust gases from the rocket further compress the outer flow and utilise this additional reaction mass. It is a hybrid of a ramjet and conventional rocket. [59.]
- Turborocket: Usually consist of a gas generator, which provides compressed air for a combustion chamber, where fuel is added and the hot exhaust leaves the nozzle as a rocket. At higher altitudes and speeds or in the absence of atmospheric oxygen, an on board supply can be used to supply the oxidiser for the rocket engine. [60.]
- Turboramjet: a potential solution to solve the problem of the lack of low speed thrust from the ramjet engines. It is built up from an inner turbojet with an outer ring of ramjet duct. At low speeds an internal turbojet is utilized to accelerate while at high speeds, an outer ramjet is used to generate the high thrust required.

The North Aviation Griffon II was the first aircraft in the world to use a turboramjet in 1953 [61.]. There are variations of the concept, for example the ATREX engine is an expander cycle turboramjet [62.].

- Detonation engines: There are various types of detonation engines: standing detonation [63.], pulse detonation [64.][65.] and continuous (rotating) [66.] detonation engines. Detonation engines, similar to ramjets require a minimum flight speed to work, but it is claimed that continuous detonation wave engines are usable at low speed as well.
- Rocket Based Combined Cycle: Utilizes rocket propulsion at low speeds, while at higher speeds, the system switches to a scramjet mode for more efficient propulsion. [67.][68.]
- Turbine Based Combined Cycle: A combined system, which relies on a turbojet or low bypass ratio turbofan at speeds up to about Mach 3, after which a ramjet takes over to provide thrust. One example is the Lockheed Martin SR-72 currently under development. Figure 15 shows the concept of the combined cycle system of the SR-72.

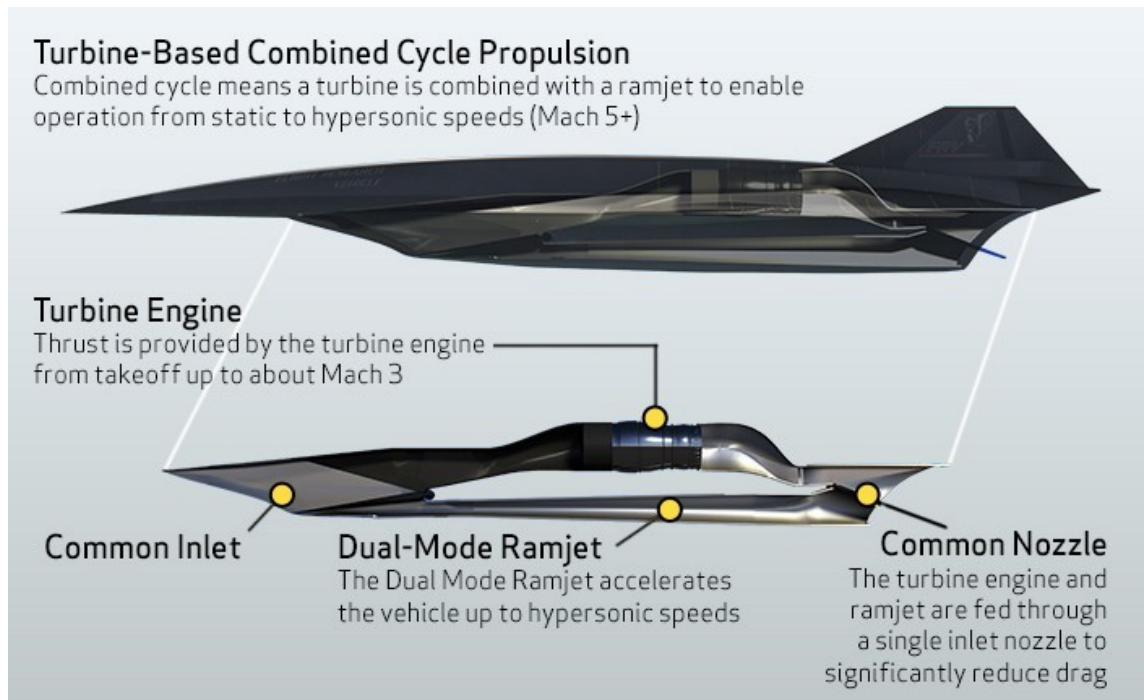


Figure 15: SR-72 Turbine-based combined cycle propulsion (source: [69.])

4.2.2 Additional methods

There are some additional methods to produce extra propulsive force or reduce drag on an aircraft. Some of these methods are still at an early stage of development, and as such might turn out to be non-feasible solutions. These methods presented cannot provide adequate propulsion on their own, rather they have to be combined with existing systems.

- **In flight air collection:** by not carrying the oxidizer on board, but collecting it from the atmosphere, significant take-off weight reductions could be achieved. This atmospheric oxygen can be stored in some form on-board to be further used as the oxidizer. The novel SABRE [70.] engine being developed for the Skylon space launcher utilizes an evolved version of their original Liquid Air Cycle Engine (LACE) system.
- **External supersonic burning:** a potential drag reduction phenomenon, recently discovered, Based on Froning and Roach, [71.], it is claimed that inviscid drag could be reduced up to 55 percent compared to baseline configuration. Injecting

fuel into the external flow increases both the shock wave intensity (additional drag), and vehicle base pressures (reduces drag). Whether the injection results in a net drag increase or loss depends on the position of the heat addition. According to the studies, aft positions are favourable.

- **Precooled jet:** any airbreather propulsion system could benefit from the utilization of precooling. According to Taguchi et al. [72.] A pre-cooled turbojet could propel a hypersonic transport up to the speeds of Mach 5.
- **Magnetohydrodynamic assist:** MHD bypass [73.] could be utilised to add additional performance for an airbreather engine. The working principle is to ionize air and use electromagnets to further accelerate the flow, resulting in increased thrust. The technology was originally used on the Russian AJAX [74.] scramjet demonstrator.
- **Reformed fuel:** Also featured in the AJAX concept [79.], this technology involves the reformation of hydrocarbon fuels, resulting in a superior ignition quality compared to pure hydrogen. Also the energy required for the reforming process acts as a heat sink for thermal protection.
- **Thrust augmented nozzle:** Also known as afterburning nozzle, part of the propellant flow is combusted in the rocket's nozzle [75.]. It is utilized at sea level and turned off at higher altitudes.
- **Altitude compensating nozzle:** this type of nozzle alters the exhaust flow of the rocket as it changes altitude, ensuring that the propulsion system always works at its design expansion ratio, thus reducing losses. Although variable geometry is a solution, it usually imposes a severe mass penalty on the vehicle. A special version is an aerospike nozzle [76.], using a central "spike" or "plug" to which the exhaust gas flow attaches itself, while their outer boundary is the atmosphere, resulting in an inverted bell nozzle. They should achieve altitude compensation with a much lower mass penalty compared to variable geometry nozzles.

- **“Spikes”**: A slender body protruding from the nose of the vehicle, according to investigations, could provide drag reduction or even thermal protection for the airframe. The various types of spikes are: “plain” [80.], “flame”, “laser” and “counter flow” [79.]. Some designs have claimed to also reduce the sonic signature of the vehicle [81.]. Example spike geometries and their effects on the flow are shown in Figure 16.

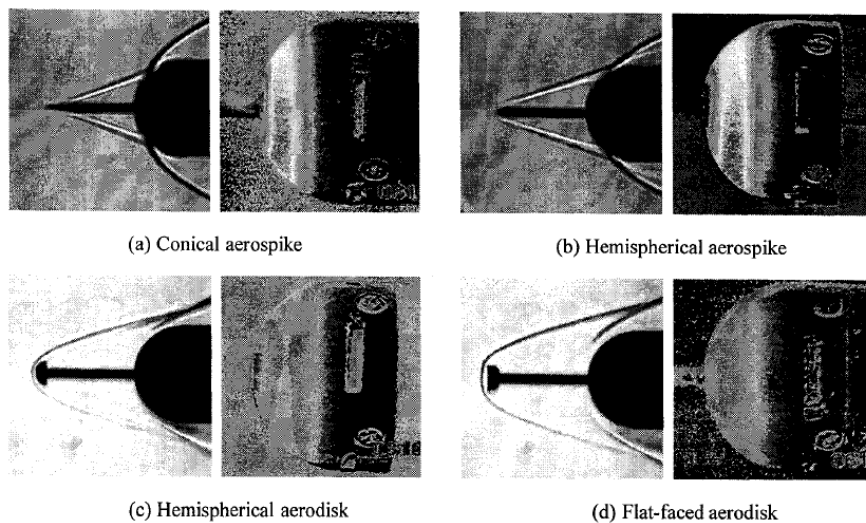


Figure 16: Schlieren flowfield photographs and surface temperature distributions for various spike geometries (source: [79.]

For further reading, a summary of the various propulsion systems can be found in the works of Pratt and Heiser [61.] or Hasselrot and Montgomerie [77.] or Varvill and Bond [78.].

4.3 Structures

Although the structure of a hypersonic vehicle is not necessarily subject to the extreme g loads, as in the case of a fighter aircraft, it is still a very complex design. There is intensive heat load generated during flight, both for Transports and Launchers. The main difference is in the distribution and peak heat flux. The heat generated is proportional to the atmospheric density and to the third power of velocity. However this heat is generated

in the air molecules, and only a fraction of it reaches the vehicle: from a few percentage points up to about 50%.

Transports generate constant, but fairly low (compared to Launchers) heat flux during their relatively long hypersonic cruise phase, due to their sleek shapes and sharp geometries. The shockwave is ideally still attached to the vehicle to reduce drag, and for a waverider also to provide lift. On the contrary, during the atmospheric re-entry phase, launchers experience brief but very intense heat loads, thus the common designs incorporate relatively blunt features to detach the shockwave from the structure, effectively using it as a shield to, ideally, prevent the formation high enthalpy turbulent flow near the surface, which would pass an extreme amount of heat into the structure through convection.

The main heat transfer mechanism to the vehicles is convection. For launchers there is another primary mechanism due to catalytic reaction on the vehicle surface, which can account for up to 40% of stagnation heat loads. In addition to this, depending on the atmosphere, radiation from the superheated plasma surrounding the aircraft could also transfer significant amount of heat into the vehicles. This is typically an issue at high entry speeds (10km/s and above) or in extra-terrestrial atmospheres, such as Mars or Venus (on the other hand, on Jupiter radiation heat loads are less significant). Transports experience different flow conditions. They normally operate at lower altitudes (30-40 km), thus at higher Reynolds numbers and turbulent flow conditions, which significantly increase the convective heat transfer coefficient. However, take note that their speed, and thus air temperature, is lower than for a launcher, thus overall heat flux is smaller.

Due to these high heat loads many commonly used aerospace materials might not be available for the designers, unless they are combined with Thermal Protection Systems (TPS). The TPS design requires the designers to conduct complicated aero-thermo-

elastic simulations, also accounting for chemistry, depending on the type of TPS material.

4.3.1 Types of TPS

A hypersonic vehicle's structure from a thermal protection point of view can be the following:

- **Hot structure:** there is no separate TPS, rather the metallic airframe (usually manufactured from exotic alloys, usually Nickel based superalloys) is capable of withstanding loads at elevated temperatures. A typical example is the SR-71 Blackbird.
- **Cold structure:** An external TPS covers the internal load carrying airframe, which in return can be made from more conventional materials. Two main types exist:
 - **Active cooled:** a coolant flow under the thermal protective outer skin of the vehicle is responsible for absorbing heat, and thus maintaining temperature at acceptable levels. The most commonly used heat sink is cryogenic fuel.
 - **Ablative:** the outer skin of the vehicle thermally degrades under high heat flux loads. This decomposition frees gases which act as a thin insulation layer on the surface. Also, due to this ablation, the upper layers of the TPS material becomes porous, further improving insulation capability. Their drawback is limited (short) lifespan, and the need for meticulous and expensive inspection and maintenance procedures. Typical example is the Apollo heat shield.

Normally a hypersonic vehicle utilizes a combination of different TPS materials. The Space Shuttle's cover for example used 6 different materials, which all had different thermal properties. The X-37 builds on the legacy of the Space Shuttle, employing a

similar concept in TPS, but with more advanced material technology. A close up image shown in Figure 17 shows the various TPS components the X-37.



Figure 17: X-37 Thermal protection systems (source: online)

4.3.2 TPS Materials

The main types of materials used are metal alloys, composites and ceramics. There are also non-load carrying TPS used in the form of flexible blankets. The current and most promising future TPS materials are the following:

Table 5: Thermal Protection System material properties (*Based on Space Shuttle)

| Category | Name | Maximum temperature [°C] | Mass |
|---------------------------------|--|--------------------------|--------------------------------------|
| Ultra High Temperature Ceramics | Hafnium / Zirconium Diboride (SHARP) | 1200-1600 [83.] [84.] | 10500 / 6085 kg/m ³ [86.] |
| | HRSI / LRSI (High/Low Temperature Reusable Surface Insulation) | 1300/ 650 [10.] | *9.2 / 4 kg/m ² |

| | | | |
|--------------------------|---|-----------------|-----------------------------------|
| Composites | Reinforced carbon-carbon composites | 1500 [10.] | *44.7 kg/m ² |
| | TUFROC (Toughened Uni-piece Fibrous Reinforced Oxidation-resistant Composite) | 1700 [84.][92.] | 400 kg/m ³ |
| Metallic TPS: | γ-TiAl | 900 [83.] | 3800 kg/m ³ [87.] |
| | Ni based ODS (oxide dispersion strengthened alloys) | 1200 [10.] | 7500-8300 kg/m ³ [88.] |
| | Inconel, typical properties | 1400 | 8410 kg/m ³ |
| Flexible blankets | SPFI (Surface Protected Felt Insulation) | 1200 [83.] | ND |
| | FRSI (Flexible Reusable Surface Insulation) | 400 [10.][82.] | *1.6 kg/m ² |

As an overview, most of the materials used for current aircraft primary structure cannot normally exceed 400 K with active cooling, 367K being the usual limit for conventional aluminium alloys. Hot structures on high speed vehicles are usually limited to about 800K, while insulated structures can have surfaces temperatures up to 1200 K.

Hafnium/Zirconium Diboride are ultra-high temperature ceramics under active development for heat shield applications. They have the highest melting point of known ceramics (above 3200 °C) and they have very good oxidation resistance. Due to this, they can be used for more advanced shapes such as sharp leading edges or sharp nosecones. Their main drawback is the lack of economical processing capability.

High/Low Temperature Reusable Surface Insulation are the ceramic tiles installed on most of the windward surface area of the now retired Space Shuttle. HTRSI are the black and LTRSI are the white tiles. The low temperature white tiles are coloured to reflect most of the solar radiation when in orbit, while the black ones absorb, thus also emit more heat during re-entry. The material of the insulation tiles is known as Silicon Fibrous Refractory Composite Insulation 12 (FRCI 12). It is patented by NASA [89.]. The insulation is made from aluminoborosilicate and silica fibres. Silica has good long term high temperature life, and technically acts as a matrix for the more refractory

aluminoborosilicate, which couldn't be easily shaped by itself, but is capable of sustaining higher temperatures. It is a low density insulation with improved strength and temperature capabilities to prior state of the art insulations. As their main disadvantage, the tragedy of the Space Shuttle Columbia shows that even limited damage to the TPS could lead disaster [90.]. Ceramic TPS materials tend to be fairly brittle, even small objects could cause significant damage, especially at the high speeds that the vehicles are travelling at, so careful inspection is a must before and after launch to evaluate their integrity. Furthermore, many TPS materials, such as the insulation blankets and tiles of the Space Shuttle, are hygroscopic and thus require continuous effort to waterproof them.

Reinforced Carbon-Carbon composites are built up using carbon fibres, embedded in an all-carbon matrix. This approach combines the strength of the fibres with the refractory capabilities of the matrix. Further advantages include dimensional stability and low outgassing; both essential for space applications. RCC can be used to construct complex geometries, such as the leading edges of lifting surfaces. Careful combination of matrix material and fibre types are required to avoid brittleness issues in the finished component. [91.]

Toughened Uni-piece Fibrous Reinforced Oxidation-resistant Composite is a NASA innovation, developed for space applications but now finds its use in various commercial applications such as racing cars, turbines or furnaces. The technology is based on a two-piece construction: an exposed surface cap with a specialist coating, covering an insulator base, also with specialist coating. The cap is built-up from ROCCI (Refractory Oxidation Resistant Ceramic Carbon Insulation) and its purpose provides dimensional stability for components such as leading edges or nosecones. The insulation is TUFI (Toughened Uni-piece Fibrous Insulation) treated AETB (Alumina Enhanced Thermal Barrier). It was originally developed for the X-37 wing leading edges. [92.]

Inconel is the name of a family of superalloys. It was originally developed by Wiggins Alloys in 1940s to support the development of the Whittle jet engine, and was later used on the X-15 test vehicle. They are nickel based, with chromium as the second alloying element, and depending on the actual alloy can have various other elements, such as Fe, Mo, Nb, Co and various others. They have very good oxidation and corrosion resistance even at high pressures and temperatures; heating Inconel forms a thick oxide layer on its surface passivating the alloy and preventing further deterioration.

γ -TiAl is a form of titanium superalloy, often used in metal matrix composites. It is designed to replace more conventional superalloys (such as Inconel) by providing similar structural performance, but with significantly reduced density. It also has good oxidation resistance, high modulus and thermal stability. The most common combination for MMC is γ -TiAl matrix and silicon carbide fibres. The drawbacks are poor room temperature ductility, low fracture toughness and fast fatigue crack growth rate. Metallurgical research is still ongoing to mitigate some of these drawbacks through alloying and heat correct heat treatment. [93.]

Ni based ODS (oxide dispersion strengthened) alloys are used for heat turbine blades and heat exchangers, and also for re-entry vehicles. They are formed by introducing metal oxide particles into the crystal structure, which reduce the movement along dislocations and thus the material's tendency to creep. They form a protective oxide layer similar to Inconel alloys. Their drawback is fairly high density and lower allowable temperatures than for example Inconel. Also some of the alloying metals are very expensive; refractory materials such as rhenium and ruthenium. [94.]

Surface Protected Felt Insulation was used on the Space Shuttle's leeward surfaces. It was originally developed to replace the white LRSI tiles on the upper surface. [95.] The insulation is made up of Nomex felt blankets, covered in a flexible waterproof coating and bonded to the airframe by a resin adhesive. They are light and flexible, but they can

be used only at low temperatures, thus they only cover the regions which are shadowed from the flow during re-entry.

Flexible Reusable Surface Insulation (and the improved AFRSI Advanced Flexible Reusable Surface Insulation, also known as FIB Fibrous Insulation Blankets) are blankets of layered, pure silica felt sandwiched between silica and glass fabric layers. They are semi rigid and can be made large (about 30 by 30 inches) so the number of blankets can be kept low. Their application is similar to the Nomex blankets.

Heat not only has to be absorbed by the vehicle, but also transferred away. For a transport some of the heat is absorbed by the fuel and then removed through the propulsion system. The other mechanism, which is especially important for a Space Launcher, is radiation. All bodies radiate (and absorb) heat, and the amount of radiation is proportional to the fourth power of body temperature and the surface emissivity. Emissivity depends on the surface (material, finish, and colour) the Space Shuttle has an average ϵ of 0.8 [92.]. Thus based on the input heat flux and the emissivity, the surface temperature of the vehicle is converging towards an equilibrium steady state value. This equilibrium is likely to be reached for a Transport, for its long duration flight, but might not be reached during a re-entry, it depends mainly on the vehicle and the re-entry conditions. Some designs actually rely on large heat sink masses to absorb all the heat of re-entry, without reaching equilibrium. This approach was used on the initial Mercury spacecraft, however it is a heavy solution.

4.3.3 Special thermal protection methods

Thermal protection of vehicles can be enhanced by special design features. These can be relatively simple, such as the blunt nose cone discovered by von Kármán, which enables the front shockwave to detach and absorb a fraction of the flow's energy in the process and redirect the flow.

A recent development is the feathered entry used by the SpaceShipOne family of vehicles. By changing the tail configuration the vehicle greatly increases its drag, enabling it to slow down more at higher altitudes, where the air is less dense, thus generating lower heat loads in the lower atmosphere. The only issue of this method is the low entry speed of the SpaceShipOne, which is nowhere near the velocity of an object returning from orbit (Mach 3 as compared to the Mach 25 of the Space Shuttle).

A recent result of NASA developments is the Hypersonic Inflatable Aerodynamic Decelerator (HIAD). Being part of the NASA Game Changing Technology Development Programme, it is aimed to develop a lightweight, inflatable structure capable of absorbing the heat loads present at atmospheric re-entry. It is not exclusively intended for Earth, but for any planet bearing an atmosphere. It is manufactured from Nextel, Pyrogel and Kapton, and, in theory, is usable up to 1260°C [97.]. NASA completed a successful test launch of the HIAD on the 23rd July 2012.

As it was mentioned, active cooling of a vehicle relies on some form of heat sink to absorb the generated heat loads. The usual solution is to use cryogenic fuel, which heats up in the process. The heat capacity of the fuel might not be high enough, and thus would require very high, maybe even unsustainable, flow rates especially for low density fuels such as hydrogen. To counter this problem, different concepts were developed to absorb more heat by changing the chemical structure of the coolant. Reformed fuels use part of the heat absorbed to drive an endothermic reaction inside the fuel, which would “reform” it, thus absorbing significantly more energy than just simply relying on its heat capacity. The concept was originally proposed for the Russian AJAX vehicle. According to a Joint stock company report [98.], steam reforming hydrocarbon fuel can absorb 3.3 MJ/kg as “physical cooling resource”, while the “chemical cooling resource”, the heat of the endothermic reaction is on the order of 6.6 MJ/kg. In addition to reformed fuels, other endothermic reactions such as cracking, pyrolysis or depolymerisation are also a viable option; basically the process would fracture the longer carbohydrate chains present in

the fuel, allowing the absorption of about 5 MJ/kg. As a reference, the heat sink capability of regular hydrocarbons (JP7) is in the region of 1 MJ/kg. [99.]

4.3.4 **Structure mass fraction**

In the case of a vehicle designed for space access it is vital to keep the total mass as low as possible. According to Tsiolkovsky's rocket equation, additional weight of the vehicle raises the all up mass exponentially. On the other hand, the maximum mass fraction of a vehicle is limited by the specific impulse of its propulsion system. This means, that in order for the size of the spacecraft not to escalate, the structural weight must be kept as low as possible. It is also worth noting, that the payload fraction is significantly lower than the vehicle mass fraction as shown in Table 6. The vehicle mass fraction includes the payload mass fraction, and the remainder of the all up mass is fuel. The X-37 mass is based on an estimation by Pienkowski et al [100.]. 250 kg/crew was assumed for the people, gear and provisions, where payload was not available, based on Space Launcher mass estimation methods [101.]. Lynx data is from the payload user's guide [102.].

Table 6: Payload and vehicle mass fractions

| Vehicle name | Payload mass [t] | Vehicle mass (including payload) [t] | All up mass [t] | Payload mass fraction [%] | Vehicle mass fraction [%] |
|--------------------------|------------------|--------------------------------------|-----------------|---------------------------|---------------------------|
| Existing Vehicles | | | | | |
| X-37B – Atlas V | No Data | 4.4 | 334 | No Data | 1.32 |
| Space Shuttle | 24.4 | 123 | 2041 | 1.20 | 6.03 |
| Buran | 30 | 105 | 2375 | 1.26 | 4.42 |
| Saturn V – LEO | 118 | 301.6 | 2970 | 3.97 | 10.15 |
| Saturn V – Apollo 11 | 45.7 | 229.3 | 2970 | 1.54 | 7.72 |
| Delta IV Heavy – LEO | 23 | 105.7 | 733 | 3.14 | 14.40 |
| Soyuz – LEO | 7.8 | 32 | 308 | 2.53 | 10.39 |
| Vehicle Concepts | | | | | |
| Skylon | 15 | 68 | 345 | 4.35 | 19.71 |
| Dream Chaser – Atlas V | 1.75 (7 crew) | 11.3 | 334 | 0.50 | 3.38 |
| Lynx-II (Sub-orbital) | .28 | No Data | 5.2 | 5.38 | No Data |

4.4 Systems

The systems onboard a hypersonic vehicle are a combination of traditional aircraft-like systems, and those used on current launchers and spacecraft. The systems are of varying technology readiness levels: some, like avionics, fuel or landing system are readily available today. Others, especially those mentioned in the previous chapter, such as propulsion and thermal protection system, still require considerable research effort.

4.5 Reliability

If hypersonic flight and space access is to become an everyday activity like today's airliners, reliability has to undergo a significant improvement. The main barrier in front of raising reliability today is the expendable nature of the launchers: everything has to work perfectly for the first time, there is no possibility for incremental testing, and usually every malfunction or fault results in the loss of the vehicle and payload. In 1999 Parkinson [103.] investigated the cost of reliability on the launchers. According to him, at that time,

launch failure was estimated to be between 5 and 12%. This rate would be unacceptably high for a transportation system, for many reasons. Even excluding the moral issues, there is a significant economic consequence: the very high insurance cost. According to Parkinson, insurance costs for a launch can contribute up to 20% of the total launch costs.

There are challenges in predicting reliability. It is very difficult to predict reliability for non-existing or low TRL systems, such as novel propulsion concepts. Even in the case of scramjet technology, which has been under development for decades, there are only estimations for system reliability based on the few successful flight tests. These reliability figures based on technology demonstrators then need to be extrapolated to in service systems, which inevitably introduces uncertainty.

The success of a hypersonic transport, however, depends greatly on its propulsion system. In addition to systems, there is also an issue associated with operations. There is rarely any information available for exotic manoeuvres such as aerial refuelling, as they have only been conducted with military personnel, thus are seldom published. Their suitability to civilian application is questionable. Also operations such as maintenance and inspection for new structural materials are challenging to estimate.

4.6 Maintainability

Maintainability was clearly the Achilles' heel of the Space Shuttle. The Shuttle required tens of thousands of man hours between each launch, most of which could be attributed to the intricate thermal protection system, which consisted of over 30000 ceramic tiles, each requiring individual inspection.^(104.) In the case of future hypersonic transportation systems, it is imperative that maintainability is designed into the vehicle, rather than just something evaluated at the end of the design process. Improving maintenance not only reduces the turnaround time for the vehicle, but provides additional benefits when the

time and wages of the maintenance personnel is considered. Typical turnaround times are shown in Table 7.

Table 7: Typical processing times (ref: [105.],[106.],[107.],[108.],[109.])

| Vehicle | Turnaround time [days] |
|---|-------------------------------|
| Skylon (planned) | 1 |
| X-37 (source not verified) | 10-15 |
| Space Ship One (Based on X-Prize winning performance) | 5 |
| Space Shuttle (processing only) | 75 |
| HL-20 (planned average) | 46 |
| X-15 (average) | 44 |

5.0 Testing and legal issues

5.1 Certification

In the case of aircraft, authorities such as the European EASA or the US FAA provide a set of airworthiness specifications, which must be met if the vehicle is to use the airspace governed by these authorities. For spacecraft there are no international standards in existence about certification requirements and procedures. This is mostly because there are very few in existence, and up to recently, there were no civilian projects reaching anywhere near the stage of certification. The matter is further complicated by the fact, that no countries have legal claim over space, and as such specifications issued by a national agency might not be acceptable by other nations. This is especially important, as unlike conventional airspace users, a vehicle entering the atmosphere does not have an option not to travel through the airspace of other countries. Legal issues arising from this might lead to complications in future certification procedures, and can have political consequences.

There are steps taken to provide means of certification for this emerging class of vehicles but the approach taken to solve the legislation issues are different. From the EASA's point of view [110.], aerospace vehicles, that generate aerodynamic lift during their ascent fall into the airplane category defined by the ICAO Chicago convention, and thus must be certified under the EASA CS regulations. This definition excludes rockets, as they rely on the reaction force of the exhaust rather than lift from the atmosphere. The United States adopts a different approach to public space activity. The congress signed the Commercial Space Launch Amendment Act in 2004, giving power to the FAA to regulate commercial human spaceflight activity. By 2006, the FAA published its rules for public spaceflight [111.], setting standards and minimum requirements for acquiring a launch licence. Launch licensing is significantly different to the certification approach, as in the licensing case, the responsibility rests on the operator, whereas in the case of a

certification, it belongs to the certifying authority. NASA has also compiled technical standards and evaluation criteria for its Commercial Crew Program[112.].

Normally type certification is meant for aircraft produced in larger series. In the case of hypersonic vehicles, especially during the early phases, there might be only a few vehicles produced of a specific type, or maybe even just one. In this case, going through a long type certification procedure would not be desirable. Although the EASA offers the possibility of issuing a Restricted Type Certificate for special purpose vehicles, for the above reasons, commercial space companies might not want to take that route. For a small series, a Restricted Certificate of Airworthiness could be issued, based on Specific Airworthiness Specifications, but in order to maintain continuous airworthiness, the EASA would not favour this approach. The final option available today by the EASA is the Permit to Fly, but this excludes commercial operations and complex aircraft, so it would only be available for flight testing.

Licensing with the FAA is a different procedure. Anyone wishing to launch, operate or re-enter a space faring vehicle within the United States, or any person or entity local to the states must apply for a license or permit. A decision is usually made in 120 days for permits and 180 days for licenses [113.]. An experimental permit requires less paperwork, but no property or human being may be carried for compensation or hire and permitted launches are not eligible for indemnification [114.]. Initially Virgin Galactic has been flying their vehicles with FAA experimental launch permits, but has finally received a Commercial Launch License for SpaceShipOne [115.].

5.2 Flight testing and prediction methods

Reusable hypersonic vehicles represent a great step towards improving safety and reliability by allowing incremental testing of the vehicle. Although the component testing on the ground is similar for both types of vehicles, a reusable vehicle offers the chance for flight testing. It is essential to conduct this step, as tests done in wind tunnels are

based on dimensional analysis, and it is impossible to match each and every condition due to limits in size, etc. Figure 18 shows typical flight corridor and wind tunnel capabilities. Even so, CFD models must be validated, for which flight testing is the only appropriate method at whole aircraft scale. At hypersonic speeds, even the more basic theories have to be validated due to the extreme flight conditions.

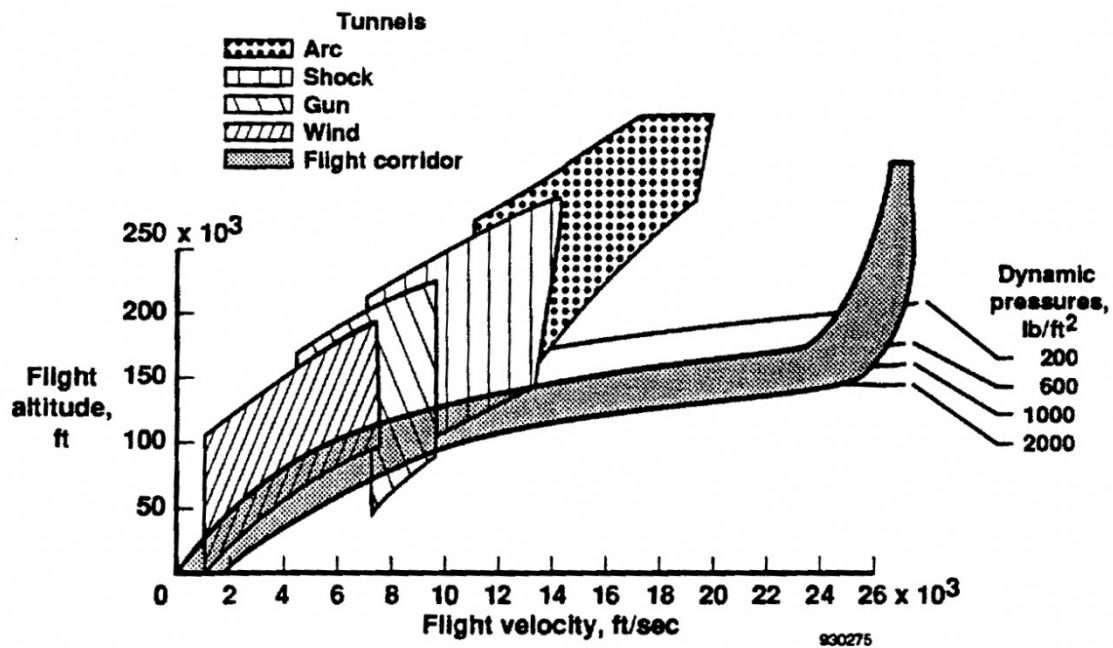


Figure 18: Existing ground test capabilities for hypersonic development (source: [80].)

Flight testing of a vehicle usually follows the following steps:

- Captive-carry, unpowered
- Captive-carry, powered
- Free-flight, unpowered
- Free-flight, powered

These steps will ensure that the flight regime is explored incrementally. For a given vehicle not all steps might be applicable, for example a test aircraft with scramjet engine can't be operated while mounted on a subsonic carrier aircraft, but is perfectly fine when launching a rocket carried test article. The test vehicle does not necessarily have to be

full-sized, sometimes captive tests are conducted using scaled down test articles. For hypersonic vehicles, there is still no global consensus on the acceptable scale, especially for scramjet propulsion systems. Aircraft mounted tests are usually conducted up to M3, while rockets can reach very high Mach numbers.

Free flight can be achieved by either aerial or similarly assisted launch or self-powered take-off, the latter normally happening at later stages of the testing. Free flight is the only way to accurately assess and validate the aerodynamics, structural and propulsion models generated during the design process. Performing free flight from assisted launch not only requires attachment, but also safe release mechanisms, requiring the carrier vehicle to be even more complex. As a benefit, the test vehicle can perform its own mission at the given flight conditions, alleviating the need for the carrier aircraft to perform the same manoeuvres.

Conducting a flight test just for the sake of flying is not the goal; meaningful data has to be collected during the flight. This process is not trivial, as the conditions during a hypersonic flight usually involve severe heating, acoustic load, oxidising atmosphere, ionised gas and local plasma conditions. The high temperatures result in chemical and/or physical changes in the measuring systems and structures, which can adversely affect the accuracy of measurements. Installing sensors is also challenging structurally, as they have to be bonded or fastened to the structure, with adequate strength, but they should not alter the stiffness or thermal integrity of the surrounding structure or intrude and alter the field of measurement. Adding the sensors, their support structure, cooling, etc. would also add mass, complexity and take away precious volume from the vehicle. Figure 19 shows the instrumentation of the Sharp Edge Flying Experiment 2 (SHEFEX2).

Overview of the Payload Tip and Instrumentation

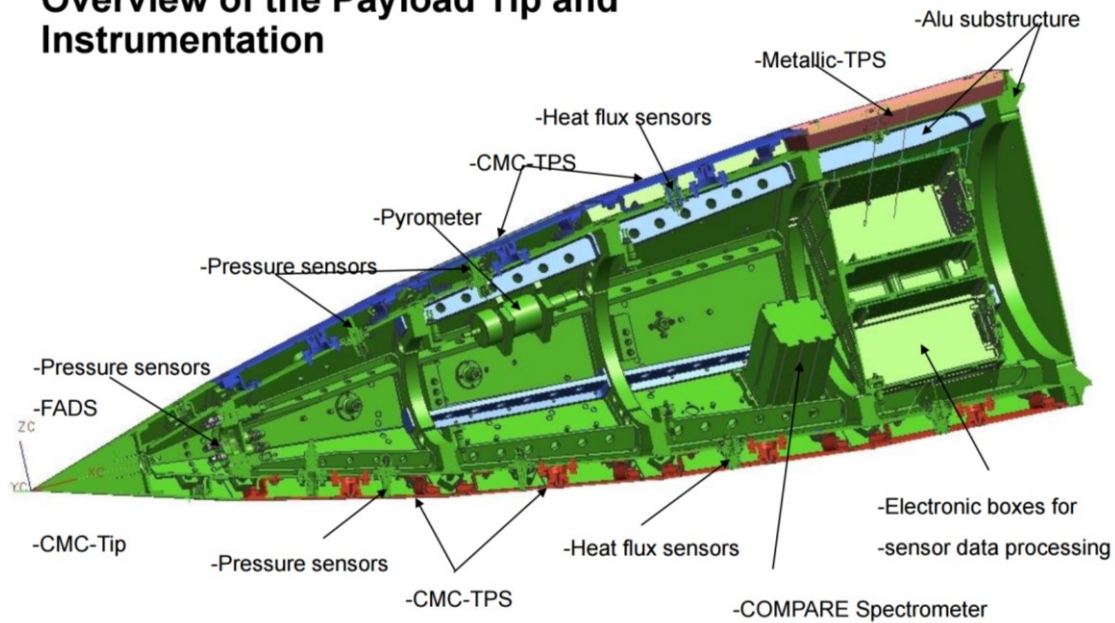


Figure 19: SHEFEX2 Overview of the Payload Tip and Instrumentation (source: [114.])

Measuring the data in itself is still not enough, it has to be recorded on-board and/or transmitted to ground stations. Data signals from measurements also have to be processed and conditioned, possibly real-time, while the signals could have very high sample rates over thousands of parameters. Planning this is especially crucial when data is just transmitted and not recorded as the telemetry system has limited bandwidth to transmit data. Transmitting the data requires antennae, which in addition to the structural challenge of mounting them have to overcome the difficulties of transmitting through potential plasma sheets or tracking the ground or satellite based receivers at high speeds.

Figure 20 highlights how essential in flight testing is, compared to predictions. The graph shows the infamous Space Shuttle body flap trim issue. Essentially it shows that during high Mach numbers (10+) the body flap was very close to its maximum deflection to provide sufficient longitudinal trim, as opposed to the predicted low deflections.

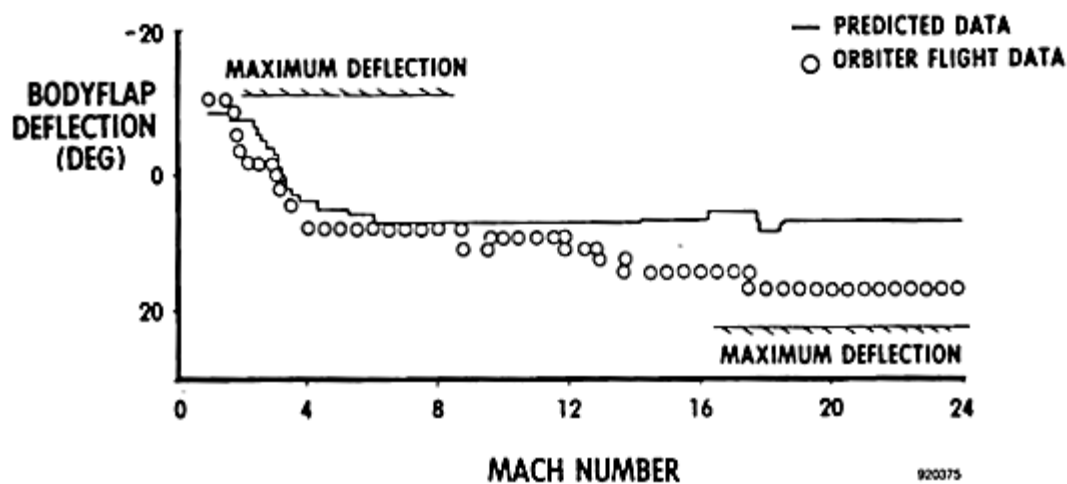


Figure 20: Longitudinal trim characteristics from STS-1 (source: [117.])

6.0 Interested companies, current projects

Table 8 presents Space Launchers and other Hypersonic Transports currently in development, along with promising concepts. Main parameters are summarized, followed by a brief description for each.

Table 8: Summary of hypersonic vehicles

| Vehicle | Country of origin | First launch or flight (planned) | Maximum altitude | Maximum speed | Payload |
|----------------------|-------------------|-----------------------------------|------------------|---------------|----------------------|
| Concept vehicles | | | | | |
| Hammer | Russia | No data | 500km | Orbital | 800kg |
| ZEHST | Europe | -2040 | 32 km | Mach 4 | 50 – 100 passengers |
| Lockheed SR-72 | USA | -2030 | No Data | Mach 6 | No Data |
| PAK-DA | Russia | 2020-2030 | No Data | Hypersonic | No Data |
| SL-12 "Vimana" | UK | -2020 | LEO | Orbital | 6000 kg |
| Skylon | UK | -2019 | 200 km+ | Orbital | 15000 kg |
| SOAR | Switzerland | 2016 (test flight) | 80 km | No Data | Up to 250kg |
| Lynx | USA | -2015 | 100km | Mach 2.7 | 1 passenger or 120kg |
| LEA | France | -2015 | No Data | Mach 8 | No Data |
| Operational vehicles | | | | | |
| New Shepard | USA | 29/04/2015 | 100 km | No Data | 11.3 kg |

| | | | | | |
|----------------------------------|---------------|------------------------|----------------|----------------|---------------------------|
| IXV | Europe | 11/02/2015 | Not Applicable | 7700 m/s | No Data |
| Orion Multi Purpose Crew Vehicle | USA | 05/12/2014 | Beyond LEO | Not Applicable | 4 passengers |
| EADS Spaceplane | Europe | 05/06/2014 (drop test) | 100 km | Over 3000 km/h | 4 passengers |
| Dream Chaser | USA | 26/10/2013 (drop test) | Not Applicable | Not Applicable | 7 passengers |
| Falcon 9 | USA | 19/09/2013 | GTO | Orbital | 13150 kg LEO, 4850 kg GTO |
| Space Ship Two | USA | 29/04/2013 | 110 km | 4200 km/h | 6 passengers |
| STIG B | USA | 06/10/2012 | 100 km | No Data | 50 kg |
| Masten Xaero | USA | 2011 | 30km | No Data | 10kg |
| Dragon | USA | 08/12/2010 | Not Applicable | Not Applicable | 3310 kg |
| X-51 | USA | 26/05/2010 | 21 km | Mach 5.1 | No Data |
| X-37 | USA | 22/04/2010 | LEO | Orbital | No Data |
| HIFIRE | Australia/USA | 07/05/2009 | Various | Hypersonic | No Data |
| Shenlong | China | 11/12/2007 (drop test) | No Data | No Data | No Data |
| X-43 Hyper-X | USA | 02/06/2001 | 33.5 km | Mach 9.6 | No Data |

The Scaled Composites Space Ship Two is the follow-up of the Ansari X-prize winning Space Ship One. Although it does not reach hypersonic speeds, it does reach the altitude of 100 km, qualifying as a space launcher. On the 30th of May 2012, the FAA has issued the launch permit for powered flights, with the intention for test flights at the end of the year. The first SpaceShipTwo aircraft, VSS Enterprise, broke up during a test flight and crashed in Mojave on 31 October 2014. The apparent reason of the accident is the premature unlocking of the vehicle's "feather" re-entry mechanism by the co-pilot, which resulted in an aerodynamic overload. The National Transportation Safety Board also highlighted the flaw in design that a single human error could result in a catastrophic hazard. [120.] A second spaceplane, VSS Voyager, is currently being built with a planned service date of 2015.



Figure 21: Scaled Composites/Virgin Galactic Space Ship Two (source: [119.])

The Orion MPCV is a reusable spacecraft intended to carry a crew of four beyond LEO to facilitate the human exploration of the Solar system. The first (unmanned) spacecraft was successfully launched on 5th December 2014, which later re-entered the atmosphere and was recovered after splashdown. Future planned missions include human exploration of an asteroid and Mars.



Figure 22: NASA Orion MPCV (source: [121.]

Reaction Engines has been pursuing the ultimate goal of SSTO space access since 1982, when the concept of HOTOL originated from BAE. After technical and funding issues, the development of HOTOL and its follow-up (Interim HOTOL, HOTOL 2) was cancelled but, after forming Reaction Engines, the concept was carried over by the conceptual designers, mitigating its original flaws, and improving the design. Their latest major achievement was the successful testing of the key components of its SABRE engine in July 2012, the company is now expanding its design department to meet the challenges associated with the completion of this major project.



Figure 23: Reaction Engines Skylon (source: [122.]

Lockheed Martin's SR-72 is an unmanned aircraft concept capable of reaching speeds up to M6. The vehicle is powered by a Turbine-Based Combined Cycle propulsion system. It is estimated to be in operation by 2030.



Figure 24: Lockheed Martin SR-72 (source: [123.]

Boeing X-37 is the still classified military UAV, built by Boeing and operated by the U.S. Air Force. The program has already achieved three successful orbital flights (first in 2010), the third vehicle spending 674 days in space [124.]. The purpose and payload of its mission, up to this date, is confidential. It has achieved the first US autonomous re-entry and landing (only second to the Soviet Buran). There was a fourth mission, OTV-4 launched on 20 May 2015, details are classified as usual.



Figure 25: Boeing/USAF X-37 (source: [125.])

SpaceX (Space Exploration Technologies Corporation) became the first company to successfully dock their Dragon Spacecraft to the International Space Station under the NASA Commercial Orbital Transportation Services (COTS) program. While the Dragon is a spacecraft, with no means to reach orbit on its own, it is intended to be fully reusable, making it similar in this respect to a hypersonic vehicle. The same company produces the Falcon 9 rocket, which according to CEO Elon Musk, will become the first fully reusable launch vehicle.

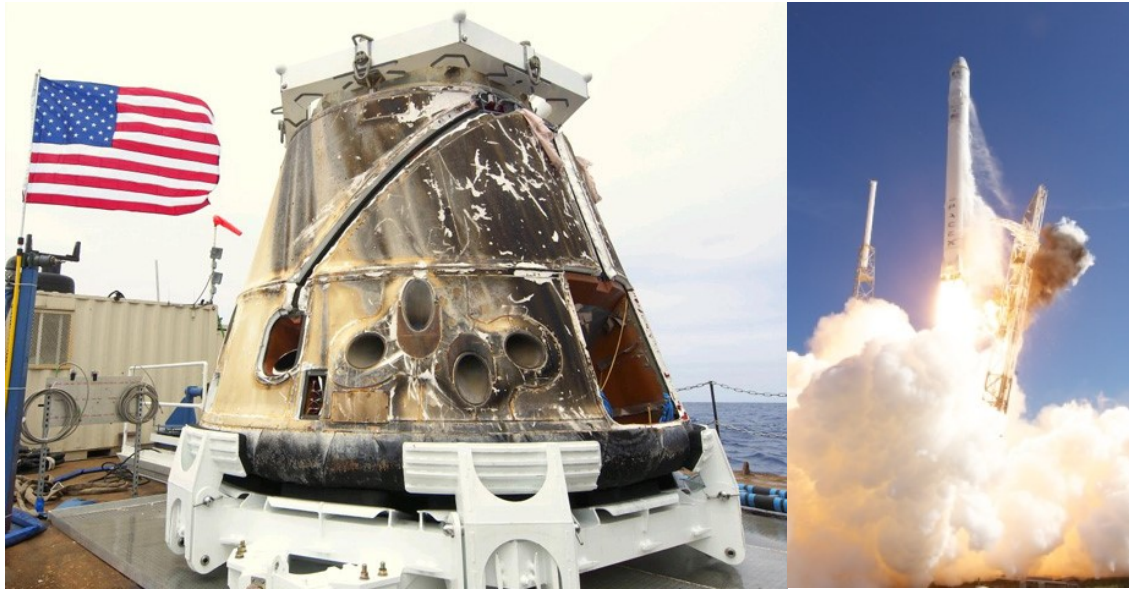


Figure 26: Space-X Dragon and Falcon 9 (source: [126.]

The Oklahoma based Rocketplane was successfully saved from closing down after it has filed for bankruptcy in 2010. Since then the company belongs to the holding company called Space Assets and is searching for investors for its six-passenger sub-orbital space vehicle. Another company founded by Chuck Lauer in 2011, called SpaceLinq, is established in Europe, with the intention of launching the same design, operating from Lelystadt Spaceport in The Netherlands. There hasn't been any word about the company since its foundation, spacelinq.nl seems to market scaled models of spacecraft, with no mention of rocketplanes whatsoever.



Figure 27: Rocketplane (source: [127.]

The Lynx is XCOR Aerospace's attempt to enter the emerging space tourism sector. They utilize reusable rocket propulsion systems to achieve single stage to orbit performance (up to 100 km). The later versions, Mark II and III will be also capable of carrying payload, to sub-orbit or an upper stage to reach orbit, respectively. In August 2012, XCOR started negotiations with NASA to launch from Kennedy Space Launch Center. Flight tests for Mk I were planned for late 2012, according to their website, the flight test program starts in 2015, aiming to reach 61 km.



Figure 28: XCOR Lynx [128.]

Armadillo Aerospace was founded by the game programmer John Carmack in 2000. They intend on developing reusable launch vehicles for space access by taking an incremental modular approach. Compared to others in the sector, their company is quite small, with some members working only part-time on the project. The philosophy is to provide simple, cheap space access, and this is achieved by investigating a variety of concepts, mostly VTVL. After acquiring the FAA launch permit in July 2012, testing of the STIG reusable rocket began. At the first attempt, the rocket only reached 90-95 km above the sea level, meaning it is still not considered to be a spacecraft. Another notable attempt was made on October 6th, 2012, where although they successfully launched STIG B, due to a flight abort, still hasn't reached space. In 2013, after the crash of the STIG-B, the company has suspended its activities. Some of the employees have formed a new company called Exos Aerospace and continue developing the space vehicles.



Figure 29: STIG B, Lunar Lander 2, Pixel (source: [129.])

The European Space Agency has developed IXV (Intermediate eXperimental Vehicle) to gather data on atmospheric re-entry, to aid the design of hypersonic vehicles of the future. The vehicle has been through drop and parachute tests, and also completed its first re-entry mission, launched on 11 February 2015.



Figure 30: ESA IXV (source: [130.]

EADS has more than one promising concept under development. The Spaceplane is a sub-orbital vehicle the size of a business jet, being able to carry four passengers to 100 km altitude, promising 3-5 minutes of zero gravity for its passengers or scientific payload. There is no update on the status of the project since 2010. The other vehicle being researched is the Zero Emission Hypersonic Transport (ZEHST). Despite its name, it is an airbreathing Mach 4 airliner, utilizing bio-fuel acquired from microalgae. It boasts a 2.5 hour flight duration from Paris to Tokyo, and is estimated to be in service by around 2050.



Figure 31: EADS Spaceplane and ZEHST (source: [131.]

Stratolaunch Systems is assembling a team of companies, who will provide low cost, reusable space access by combining their individually developed vehicles. Their plans

include the utilization of Space-X launchers air-launched from a Scaled Composites carrier aircraft. A fourth company, Dynetics will provide systems engineering and integration support for Space-X and Scaled Composites. On October 10, 2012 Stratolaunch announced the opening of a production facility at Mojave Air and Spaceport for the production of composite components of the carrier aircraft. [132.] On the 3rd of June, 2013, they partnered with Orbital Sciences Corporation to design build and operate Stratolaunch's redesigned air launch system, incorporating a scaled down version of Sierra Nevada Corporation's Dream Chaser vehicle.

Blue Origin is developing technologies to enable low cost and high reliability space access. Their New Shepard reusable crew capsule is following an incremental development approach, aiming for sub-orbital space access first, and then upgrading to full orbital capabilities. They wish to achieve this by developing the capsule and a reusable booster system to lift the capsule to a sub-orbital staging point. Both configurations are designed to take-off and land vertically. Their latest achievement was the successful crew escape system test on October 22, 2012.



Figure 32: Blue Origin New Shepard crew escape system test (source: [133.]

Sierra Nevada Corporation is developing their Dream Chaser vehicle, part of NASA's Commercial Crew Integrated Capability Program. In August 2012, the company had finished its first milestone of the CCIcap program, and it is currently at its 8th, completed

its wind tunnel testing in 2014. However in September 2014, NASA did not select the Dream Chaser for the next phase of the Commercial Crew Development Program (The two selected companies were Boeing and SpaceX).



Figure 33: Sierra Nevada Corporation Dream Chaser (source: [134.]

Masten Space Systems is developing reusable rocket VTVL solutions for low cost sub-orbital space access. The vertical lift-off and landing are inspired by the Delta Clipper Experimental's approach. Their latest achievements were the test firing of the Scimitar engine for the Xaero-B in September 2012, and the 1 km launch test of the Xaero vehicle, which ended in an unfortunate loss of the vehicle.



Figure 34: Scimitar test firing, Masten Xaero (source: [135.])

In Russia a large scale merger was performed recently in order to create a holding for the development and production of hypersonic weapons. The two companies involved are Tactical Rocket Weaponry and NPO Mashinostoyeniya. Their first step towards achieving their goal is the development of general hypersonic technology, with later plans to create the hypersonic version of the BRAHMOS Indian-Russian joint venture cruise missile. On August 27, 2012 Russia's Deputy Prime Minister Dmitry Rogozin also hinted at the development of a Russian hypersonic bomber, estimated to enter service by 2020, by the Tupolev design bureau, the alleged PAK-DA bomber. No official documents exist; Figure 35 shows a probable configuration.

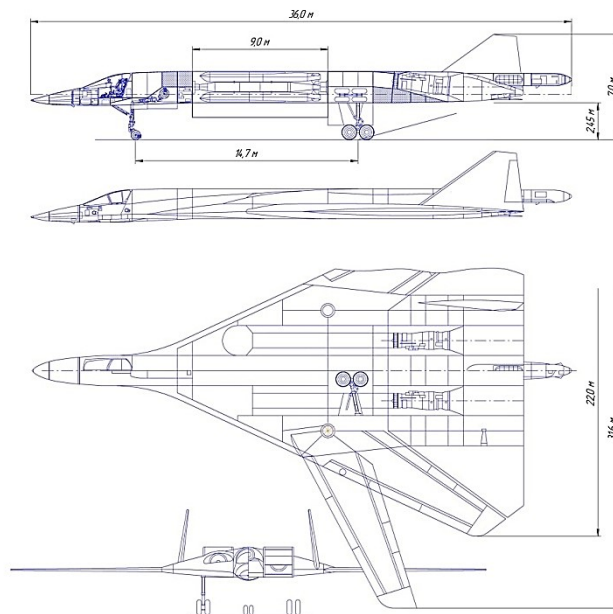


Figure 35: PAK-DA possible configuration (source: [136.])

According to Russian news portal, RIA Novosti [137.], NPO Molniya is working on a future hypersonic booster for launching satellites, designated "Hammer". It is claimed that the vehicle is capable of launching up to 800kg of payload into 200-500 km orbits, partially powered by the AL-31F turbofans of the Su-27, while the orbital stage will utilize a RD-0124 derived rocket motor. Molniya is also rumoured to be working on a space tourist vehicle along with the Myasischev Experimental Factory.

The X-51 WaveRider is being developed by a corporate effort of USAF, DARPA, NASA, Boeing and P&W Rocketdyne. It is a scramjet powered flying demonstrator utilizing the waverider principle. The first powered flight was on 26 May 2010, reaching Mach 5 and the scramjet providing thrust for about 140 seconds. The second flight was on 13 June 2011, which ended prematurely due to inlet unstart. The 3rd flight was on 14 August 2012, but also wasn't successful, the vehicle has lost control and crashed into the Pacific Ocean. The X-51's fourth and final flight was on 1 May 2013, the first flight that reached the design goals. The booster rocket accelerated the vehicle to Mach 4.8 after which it separated and the vehicle's scramjet has accelerated it further to Mach 5.1. This speed was sustained for about 210 s, making it the longest ever airbreathing hypersonic flight.



Figure 36: Boeing X-51 WaveRider (source: [138.])

The HiFiRe program is a joint effort between the Australian Defence Science and Technology Organisation (DSTO) and the United States Air Force Research Laboratory (AFRL). Their latest flight test, HiFiRE 7, was planned to be launched in June 2013,

launched via a VSB30 rocket motor from the Andoya Rocket Range in Norway. Since then there has been no information available, although an 8th and a 9th launch is planned.

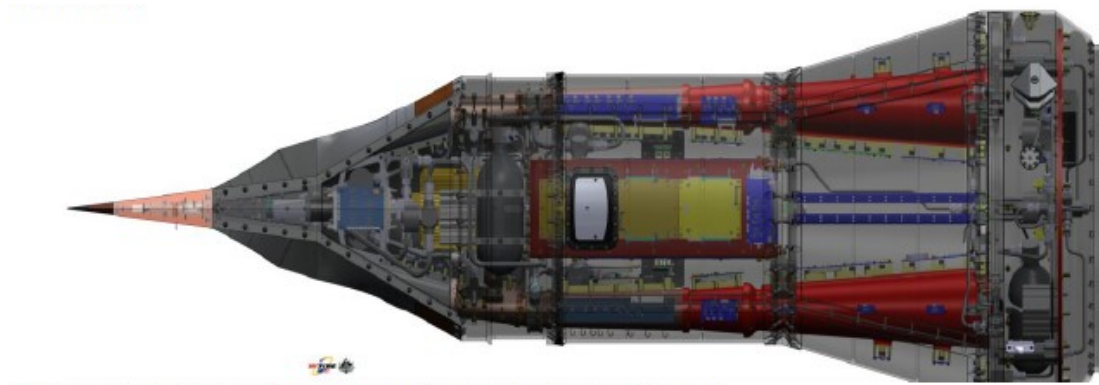


Figure 37: HIFiRE 7 semi-transparent view – Flyer with PSM attached (source: [139.]

The X-43 Hyper-X was part of NASA's hypersonic flight research program, taking on and improving the technology of the cancelled National Aerospace Plane (NASP) program. The first test vehicle, X-43A was launched from a B-52B attached to a Pegasus booster on 2nd June 2001, but was destroyed by the range safety officer when a failure occurred with the booster. The second, successful flight test was flown on the 27th March 2004. The vehicle has successfully separated from the booster, and used its scramjet engine to accelerate to Mach 6.83; the first ever vehicle operating a scramjet engine in flight. The third flight was made on 16th November 2004, reaching a world record (jet-powered) speed of Mach 9.6 and sustaining cruise for about 10 seconds. The X-43 program was retired after the 3rd test flight.



Figure 38: X-43A and Pegasus booster mounted on B-52B (source: [140.]

Another secretive space plane is the supposed Chinese version of the Boeing X-37. The vehicle is known as Shenlong (meaning Divine Dragon). According to data available it is an air launched space launch vehicle however information is scarce and mainly speculative.



Figure 39: Possible image of Shenlong carried under a Chinese H-6 bomber (source: [141.]

The LEA hypersonic demonstrator is being developed by Onera Corporation in France. Full scale wind tunnel tests were supposed to start in September 2012, with plans to

flight test in cooperation with the Russian TsAGI in 2013-2015. There has been no word from the project since 2012.

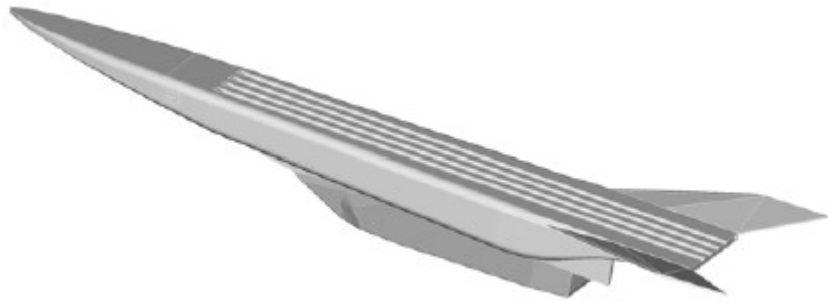


Figure 40: CAD model of the LEA vehicle (source: [142.]

Swiss Space Systems is developing the SOAR sub-orbital spaceplane to deploy small, up to 250kg satellites into LEO. The spaceplane will be launched from a 0g certified Airbus A300, will be fully reusable and will rely on standard fuels according to predictions.



Figure 41: Swiss Space Systems SOAR and Zero-G A300 (source: [143.]

Cranfield University has conducted a study on an Advanced Space Transportation Reusable Orbiter. The vehicle, SL-12 “Vimana” is a hypersonic TSTO upper stage concept vehicle. It was used as a baseline for Cranfield University’s study, which progressed the design from conceptual through to the preliminary design phase.



Figure 42: Cranfield University SL-12

There are more programs, not necessarily to develop a new vehicle, but for advancing general hypersonic technology. Part of the NASA Fundamental Aeronautics program aims to progress the knowledge and enable hypersonic flight in two different areas: hypersonic airbreathing vehicles and large mass planetary entry vehicles. The X-51 and HiFiRE test programs are also under the Fundamental Aeronautics program.

7.0 Conclusions

In conclusion, it can be said, that although hypersonic vehicles show some similarity to other classes of aircraft, especially to supersonic aircraft, there are many unique features which make the design of hypersonic vehicles particularly challenging.

When comparing the design of Space Launchers and Hypersonic Transports, there are similar requirements, but there are also distinct differences. Although they both operate at high Mach numbers, Transports types generally keep to lower hypersonic speeds,

typically Mach 5, while Launchers can reach significantly higher speeds, up to Mach 25. Due to this difference, their shapes are also significantly different. Transports tend to have a sleeker, sharper geometry, as they sustain high speeds in the atmosphere, thus minimizing drag is important. Many designs also adopt the waverider configuration; here the shockwave generates additional lift. Launchers tend to be blunter, relying on a detached bow shockwave to decelerate as quickly as possible, and reduce the heat flux into the vehicle.

Operational issues were highlighted, including typical missions, market opportunities and environmental effects, both global and local. Main technological issues were also investigated, including aerodynamics in the high speed flow regimes, propulsion and structures. Power plant concepts applicable for this flight regime were also identified, along with their benefits and limitations, highlighting potential future game changing technologies. Testing and legal issues were discussed, with recent examples and different approaches to certification.

Based on the reviewed information, the main challenges are primarily twofold; low structural mass, while maintaining vehicle integrity and structural stiffness, and highly efficient, high thrust powerplants. Also of great concern are the heat loads experienced during the hypersonic parts of the flights, especially during atmospheric re-entry. Key technologies to overcome these challenges are under development: novel propulsion systems, including pre-cooled turbojets, scramjets and combined cycle/hybrid systems. New TPS materials are being developed; metallic, ceramic and composite that are lighter, tougher and can resist higher temperatures than ever before. Due to fundamental research and flight test programs, the knowledge of hypersonic flow phenomena is expanded continuously, and increasing computational capacity is enabling the simulation of ever more complex and large scale problems.

As it can be seen, the challenges regarding hypersonic flight are many and complex, but it is now achievable with increasing efficiency. Successful vehicles not only have to overcome technical challenges, but also a range of certification and political issues. Unlike in previous decades, there is now much greater involvement of the private sector in the design of hypersonic vehicles, which is beneficial for the development and proliferation of new technologies.

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